Provenance and Evolution of the Yangtze River constrained by Detrital Minerals

Xilin Sun
孙习林

VRIJE UNIVERSITEIT AMSTERDAM
Members of the dissertation committee:

Prof. R.T. (Ronald) van Balen  
Dr. C.J. (Kay) Beets  
Prof. Huaning Qiu  
Prof. Gert Jan Weltje  
Prof. Sean Willett.

The research in this dissertation was supported by a fellowship (201206410036) from the China Scholarship Council. This work was supported by the argon geochronology laboratory of the VU University Amsterdam. This study is financially supported by the National Natural Science Foundation of China (41671011 and 41672355).

Layout & Cover design: Xilin Sun  
Printed by: Ipskamp Printing  

Back cover: photo by Xilin Sun.
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ACADEMISCH PROEFSCHRIFT

ter verkrijging van de graad Doctor aan
de Vrije Universiteit Amsterdam,
op gezag van de rector magnificus
prof.dr. V. Subramaniam,
in het openbaar te verdedigen
ten overstaan van de promotiecommissie
van de Faculteit der Bètawetenschappen
op dinsdag 3 oktober 2017 om 9.45 uur
in het auditorium van de universiteit,
De Boelelaan 1105

Door
Xilin Sun
geboren te Enshi, China
promotor: prof.dr. J.R. Wijbrans

copromotor: dr. K.F. Kuiper
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Samenvatting

De botsing tussen de tektonische platen van India en Azië zorgde voor het ontstaan van het Tibetaans Plateau en op zijn beurt, de versterking van de Oost-Aziatische moesson. Tektonische deformatie en veranderingen in de topografie van het Oost-Tibetaans Plateau controleerden de ontwikkeling van de drainage patronen in dit gebied. De Yangtze rivier, een van de grootste riviern in Azië, is ontwikkeld langs een reeks gecompliceerde stroomonthoofdingen. De evolutie van de Yangtze rivier wordt bepaald door de tektonische geschiedenis van het Tibetaans Plateau en klimaatveranderingen die samenhangen met het omhoogkomen van Tibet. De exacte ouderdom en evolutie van de Yangtze rivier wordt al nagenoeg een eeuw bediscussieerd. In deze studie onderzoek ik de ontstaansgeschiedenis van de Yangtze rivier. De meest vooraanstaande doelen van dit onderzoek zijn 1) het bepalen van de herkomst van het riviersediment in verschillende bekkens langs het huidige traject van de Yangtze rivier en 2) de reconstructie van de ontwikkeling van de Yangtze rivier.

Deze studie maakt van $^{40}$Ar/$^{39}$Ar dateringen op muscoviet en biotiet om de evolutie van de Yangtze rivier te reconstrueren. In hoofdstuk 2 en 3 wordt deze methode getest. Gebaseerd op veranderingen in de herkomst van het sediment door de tijd kan de ontwikkeling van de Yangtze rivier gereconstrueerd worden. Er wordt voornamelijk gebruik gemaakt van $^{40}$Ar/$^{39}$Ar dateringen van detritisch muscoviet en biotiet om de oorsprong van het sediment vast te stellen. In hoofdstuk 2 wordt bepaald of de $^{40}$Ar/$^{39}$Ar dateringen op muscoviet en biotiet gebruikt kunnen worden om de herkomst van het sediment te bepalen. De $^{40}$Ar/$^{39}$Ar ouderdommen van detritisch muscoviet en biotiet in 19 zand monsters uit rivieren die hun oorsprong vinden in de oostelijke Alpen worden vergeleken met de gepubliceerde ouderdommen van het grondgesteente in de brongebieden. De detritische ouderdommen zijn overeenkomstig met de ouderdommen van het grondgesteente in de sedimentaire brongebieden, hetgeen de indruk wekt dat $^{40}$Ar/$^{39}$Ar dateringen op muscoviet en biotiet bruikbare methodes zijn om de brongebieden van sedimenten te achterhalen. In hoofdstuk 4-6 worden pseudo-recente monsters van sedimentaire bekkens in het Yangtze rivier bekken vergeleken met monsters uit invloedrijke zijrivieren om de herkomst van de sedimenten in de bekken van de Yangtze rivier te bepalen. Echter, het sedimenttransport en de erosiepatronen in de Yangtze rivieren kunnen sterk beïnvloed worden door menselijke activiteit. In hoofdstuk 3 worden de ouderdommen van muscoviet in sediment van verschillende zijrivieren vergeleken met ouderdomsbepalingen aan gesuspendeerd sediment in de Yangtze rivier. De muscoviet ouderdommen van de zijrivieren en de ouderdomsmetingen aan gesuspendeerd sediment dat wordt opgevangen in meetstations langs de Yangtze rivier verschillen significant. De verschillen tussen de berekeningen van sediment toevoer en actuele toevoer data reflecteren ‘jonge’ en ‘oude’ erosie patronen, omdat muscoviet korrels met een grootte tussen 200-500µm een stuk langzamer getransporteerd worden dan het gesuspendeerd sediment in het complexe systeem van rivieren en meren langs de Yangtze. Het gesuspendeerde sediment reflecteert ‘jonge’ erosie patronen die het resultaat zijn van menselijke activiteit, terwijl de muscoviet ouderdommen de oorspronkelijke ‘oude’ erosie patronen laten zien. We concluderen daarom dat muscoviet en biotiet $^{40}$Ar/$^{39}$Ar datering een mogelijk krachtig hulpmiddel is in de reconstructie van de ontwikkeling van de Yangtze rivier.

Hoofdstuk 4 concentreert zich op Pliocene sedimenten van twee kernen in het Jianghan bekken. Muscoviet $^{40}$Ar/$^{39}$Ar dateringen, zirkoon U-Pb dateringen en de
geochemische samenstelling van de sedimenten wordt gebruikt om de oorsprong van de Pliocene sedimenten te achterhalen. Deze data laten zien dat de bovenstroom Yangtze rivier verantwoordelijk is voor de sedimenttoevoer naar het Jiaghan bekken tot 3,5 Ma, wat erop duidt dat de Drie Kloven gevormd zijn voor 3,5 Ma. De sedimenten in de bestudeerde kernen uit het Jianghan bekken zijn echter niet ouder dan 4 Ma. Om toch informatie te verkrijgen over sedimenten ouder dan 4 Ma, zijn laat Oligoceen tot Midden Miocene sedimenten in het lagere bereik van de Yangtze rivier bij Nanjing verzameld (Hoofdstuk 5). De muscoviet en biotiet \(^{40}\text{Ar}/^{39}\text{Ar}\) ouderdommen, in combinatie met de geochemische samenstelling van muscoviet in deze monsters, laten zien dat een kleine hoeveelheid sediment van de Qingyi rivier aan het lagere bereik van de Yangtze rivier is toegevoegd. Dit suggereert dat de Drie Kloven aan het lagere bereik van de Yangtze rivier is toegevoegd. De sedimenten in de bestudeerde kernen uit het Jianghan bekken zijn echter niet ouder dan 4 Ma. Om toch informatie te verkrijgen over sedimenten ouder dan 4 Ma, zijn laat Oligoceen tot Midden Miocene sedimenten in het lagere bereik van de Yangtze rivier bij Nanjing verzameld (Hoofdstuk 5). De muscoviet en biotiet \(^{40}\text{Ar}/^{39}\text{Ar}\) ouderdommen, in combinatie met de geochemische samenstelling van muscoviet in deze monsters, laten zien dat een kleine hoeveelheid sediment van de Qingyi rivier aan het lagere bereik van de Yangtze rivier is toegevoegd. Dit suggereert dat de Drie Kloven aan het lagere bereik van de Yangtze rivier is toegevoegd.

De belangrijkste conclusies van dit onderzoek zijn:

Moderne sedimenten van rivieren die hun oorsprong vinden in de Oostelijke Alpen en de Yangtze rivier impliceren dat detritische muscoviet en biotiet \(^{40}\text{Ar}/^{39}\text{Ar}\) dateringen belangrijke hulpmiddelen zijn die gebruikt kunnen worden om de evolutie van de Yangtze rivier te achterhalen.

Ouderdomsbepalingen aan pseudo-recente sedimenten van de midden- en onder Yangtze rivier suggereren dat de Drie Kloven tussen 36,5 Ma en 22,9 Ma gevormd zijn.


De ontwikkeling van de Yangtze rivier hangt nauw samen met het omhoogkomen van het Tibetaans Plateau en de versterking van de Oost-Aziatische moesson.
The collision of India and Asia caused the growth of the Tibetan Plateau and, in turn, the intensification of the East Asia monsoon. Deformation and changes in the topography of the eastern Tibetan Plateau controlled the development of the drainage patterns in this area. The Yangtze River, one of the largest rivers in Asia, evolved as a series of complicated river capture events. The evolution of the Yangtze River is controlled by the tectonic history of the eastern Tibetan Plateau and climate changes induced by uplift of Tibet. Its exact age and evolution has been vigorously debated for almost a century. In this study I investigate the formation history of the Yangtze River. The main objectives of this thesis are 1) to constrain sediment provenance in various sedimentary basins along the current path of the Yangtze River, and 2) to reconstruct the development of the Yangtze River.

In chapters 2 and 3 the viability of using muscovite and biotite $^{40}\text{Ar} / ^{39}\text{Ar}$ dating to study the evolution of the Yangtze River was tested. The development of the Yangtze River can be reconstructed based on the spatial and temporal changes in sediment provenance. We use mainly $^{40}\text{Ar} / ^{39}\text{Ar}$ ages of detrital muscovite and biotite to constrain sediment provenance. The feasibility of using $^{40}\text{Ar} / ^{39}\text{Ar}$ ages of detrital muscovite and biotite grains to identify sediment provenance was accessed in chapter 2. The detrital muscovite and biotite ages of 19 sand samples from rivers draining the eastern Alps were compared with published bedrock ages. The detrital ages are generally consistent with bedrock ages in the source areas, which suggests that muscovite and biotite $^{40}\text{Ar} / ^{39}\text{Ar}$ dating are powerful provenance tools. Pre-recent samples from sedimentary basins in the Yangtze River basin were compared with samples from the major tributaries of the Yangtze to constrain sediment provenance in chapters 4-6. However, the sediment transport and erosion patterns in the Yangtze can be strongly influenced by human activities. In chapter 3 muscovite ages and suspended sediment data from gauging stations along the Yangtze River show that the sediment contribution from the various tributaries varies significantly. This mismatch reflects “old” and “young” erosion patterns because medium sized (200-500µm) muscovite grains are transported much more slowly than suspended sediment in the complex river-lake system of the Yangtze River. The suspended sediment records a “young” erosion pattern controlled by human activities, whereas muscovite ages reflect an unaffected “old” erosion pattern. We conclude, therefore, that muscovite and biotite $^{40}\text{Ar} / ^{39}\text{Ar}$ dating are potentially powerful sediment provenance tools for reconstructing the evolution of the Yangtze River.

Chapter 4 focuses on Pliocene sediments from two cores in the Jianghan Basin. Muscovite $^{40}\text{Ar} / ^{39}\text{Ar}$ ages, geochemistry and zircon U-Pb ages were used to identify Pliocene sediment provenance. These data indicate that the upper Yangtze River supplied sediment to the Jianghan Basin prior to 3.5 Ma, suggesting that the three Gorges formed at least before ~3.5 Ma. The sediments in the studied cores from the Jianghan Basin do not extend back earlier than 4 Ma. In order to compensate for this limitation, late Oligocene to middle Miocene sediments were collected near to Nanjing in the lower reaches of the Yangtze River (Chapter 5). Muscovite and biotite $^{40}\text{Ar} / ^{39}\text{Ar}$ ages, in combination with muscovite geochemistry for these samples show that a small amount of sediment from the Qingyi River reached the lower Yangtze River, which implies that the Three Gorges was incised before ~22.9 Ma. The several kilometers of hydrocarbon-bearing shale and evaporate (56 Ma – 36.5 Ma) deposits in the Jianghan Basin preclude the routing of a large river system like the Yangtze through the Jianghan Basin before 36.5 Ma. The Three
Gorges is therefore likely to have formed sometime between 36.5 Ma and 22.9 Ma.

**Chapter 6** presents muscovite and biotite $^{40}\text{Ar}/^{39}\text{Ar}$ ages and muscovite geochemistry for samples collected from the Jianchuan and Yuanmou basins in the upper Yangtze River in order to constrain the formation of the upper Yangtze. Specifically, when the main rivers changed from a southward flow direction toward the South China Sea to an eastward flow direction toward the East China Sea. Geochronological and geochemical data for these samples suggest that the upper Jinsha River did not deliver sediment to the Red River via Jianchuan Basin, at least not before the Pliocene. Samples from the Yuanmou Basin, ~200 km east of the Jianchuan Basin, show that in the Paleogene the Yalong River flowed southward into the Red River via the Yuanmou Basin. Pliocene samples show that the connection to the Yuanmou Basin was lost sometime between the Paleogene and Pliocene.

The main conclusions of these studies are:

Modern sediments from rivers draining the Eastern Alps and the Yangtze River suggest that detrital muscovite and biotite $^{40}\text{Ar}/^{39}\text{Ar}$ dating are powerful provenance tools, which can be used to reconstruct the evolution of the Yangtze River.

Pre-recent sediments from the mid-lower Yangtze River indicate that the Three Gorges formed somewhere between 36.5 Ma and 22.9 Ma.

Data from the Jianchuan and Yuanmou basins in the upper Yangtze River indicate that the upper Yangtze River flowed southward into the Red River. The upper Yangtze changed flow direction from southward to eastward between 30 - 18 Ma.

The evolution of the Yangtze River is closely link to the uplift of the southeastern Tibetan Plateau and intensification of East Asia monsoon.
Chinese Summary

摘要

印度板块和欧亚板块的碰撞造成了青藏高原的隆升，进而引起了东亚季风的增强。在青藏高原的东部地区的变形和地貌形态的改变引起了水系形态的演化。长江是亚洲地区最大的河流，其现在的水系是在经历复杂的水系袭夺之后形成的。长江演化过程受到青藏高原底部构造活动历史和气候变化的影响。其形成的具体时间和详细过程已经争论了近一个世纪。在本研究中，我们希望确定长江的演化历史并探讨其演化历史与构造和气候的关系。因而本研究的两个主要目的是：1) 确定长江流域内一系列盆地中沉积物的物源，2) 重建长江的演化历史。

在第2和3章中，对利用碎屑白云母和黑云母$^{40}$Ar/$^{39}$Ar方法研究长江演化过程的可行性和分析。本研究中长江演化的过程是基于沉积物的物源的时空变化来进行重建的。在本研究中我们主要利用了碎屑白云母和黑云母$^{40}$Ar/$^{39}$Ar年轮来约束沉积物的物源的变化。利用白云母和黑云母的$^{40}$Ar/$^{39}$Ar年轮来约束沉积物的物源的可行性和在第2章中进行了评估。我们把从阿尔卑斯山东部地区河流中采集的19个现代河流样品的碎屑白云母和黑云母的$^{40}$Ar/$^{39}$Ar年龄和河流源区基岩的$^{40}$Ar/$^{39}$Ar年龄进行了对比。结果显示碎屑白云母的年轮基本与源区的基岩年轮一致，说明这种方法是比较有效的物源示踪工具。在第4-6章中，长江流域内盆地中的老沉积物与长江的主要支流比较来约束其沉积物物源。然而长江流域内沉积物的搬运和流域侵蚀模式受到人类的明显影响。在第3章中，依据测定的白云母数据和水文站悬浮沉积物数据所计算出的各个支流沉积物的贡献量存在着明显的差异。这种不一致反映了长江一个“老的”和“年轻的”侵蚀模式。这是由于200-500μm的白云母在长江复杂的河湖系统中的搬运速度比悬浮沉积物的搬运速度要慢得多。悬浮沉积物记录的是一个受人类活动影响明显的“年轻的”侵蚀模式，而白云母记录的是一个“老的”受人类活动影响较小的侵蚀模式。因而，白云母和黑云母都是有效的物源示踪工具而能够运用到研究长江的演化历史中。

在第4章中，利用了来自于江汉盆地两个钻孔的碎屑白云母$^{40}$Ar/$^{39}$Ar年轮和主量元素数据以及锆石的U-Pb年轮来约束上新世沉积物的物源。这些数据的综合信息显示长江上游在上新世（约3.5 Ma）之前就已经提供沉积物到江汉盆地。然而研究的两个钻孔的沉积物的年轮只是4Ma以来的，只是提供了虽然重要但是依然很年轻的约束。为了弥补这一不足，在长江下游南京附近采集了新世～中新世的沉积物（第5章）。白云母和黑云母$^{40}$Ar/$^{39}$Ar年轮以及白云母主量元素数据和显示长江上游的青衣江提供了少量沉积物到长江下游地区。这意味着三峡在22.9 Ma以及形成了。而江汉盆地中数千米的页岩和蒸发岩（56 - 36.5 Ma）不支持在此期间江汉盆地存在像现代长江这样大的河流从江汉盆地中流过。因而，三峡的形成时间应该是在36.5 - 22.9 Ma之间。

在第6章中，从长江上游的剑川盆地和元谋盆地采集了一些样品去研究长江上游的演化过程，特别是长江上游从往南流进入红河到往东流进入东海的时间。剑川盆地的白云母和黑云母年轮数据显示金沙江上游至少在上新世之前往南流通过剑川盆地流入红河。剑川盆地约200km以东的元谋盆地的白云母数据显示雅砻江曾经至少在古新世往南经元谋盆地流入红河。雅砻江至少在上新世之前已经和红河没有联
依据前面的研究论文获得如下的主要结论:

1) 东阿尔卑斯山河流和长江的现代沉积物样品显示白云母和黑云母是有效的物
源示踪工具而能够用于研究长江的演化。

2) 长江流域沉积盆地内的沉积物研究显示三峡的形成时间介于 36.5 - 22.9 Ma 之
间。

3) 长江上游的剑川和元谋盆地内的沉积物研究显示长江上游曾经在中新世之前
往南流入红河，长江上游从往南流入红河改为往东流入东中国海发生在时间在 30-18
Ma 之间。

4) 长江水系演化的过程与青藏高原东部地区的隆升以及东亚季风的增强有着紧
密的联系。
Chapter 1

Introduction
The origin of the Yangtze River drainage system is the result of a complex interplay between internal tectonics and external surface processes, climate variation and drainage pattern evolution. The exact age and evolution of the Yangtze River is strongly debated despite having been studied for almost one century. In my thesis I will try to unravel the formation history of the Yangtze, thereby addressing both the impact of tectonics and climate. In the present chapter, I will give a background on the geology of the study area, describe the aims and the tools used in this study and conclude with a brief introduction to the different chapters.

1.1 Background

The development of high topography and thickened crust in the Tibetan Plateau region commenced before continental collision between India and Asia (since ca 60~50 Ma (Hu et al., 2016; Royden et al., 2008)). The southern and central plateau rose above sea level before the late Cretaceous while parts of northern and northeastern Tibet were still below sea level (Royden et al., 2008). Subsequently, the collision between India and Asia caused the uplift of the Tibetan Plateau and west-east ward extrusion of lithosphere from central Tibet towards the southeastern Tibetan Plateau (Royden et al., 2008). Uplift of the center of the plateau started before the uplift of the south and north central plateau (Wang et al., 2014). Oxygen isotopic data of Cenozoic sediments in the center of plateau suggest that here the Tibetan Plateau had reached an elevation of more than 4km in the early Eocene or Oligocene while the northern part of plateau was located still at low elevations at that time (Rowley and Currie, 2006). As the India-Eurasia convergence continued into late Cenozoic (23-15 Ma), the Himalaya and the Qaidam basin started to uplift and reached significant elevation (Fig 1.1a). From the Late Miocene (~8 Ma), intense uplift of the Qilian Shan occurred and formed northern edge of the Tibetan Plateau (Wang et al., 2014).

Rapid eastward extrusion of a large fragment of Eurasian lithosphere from central Tibet occurred during the Eocene or Oligocene. However, the formation of the current elevation of the eastern Tibetan plateau is controversial, spanning from late Eocene, early Miocene to middle Miocene (Clark et al., 2005; Hoke et al., 2014; Li et al., 2015). The southeastern movement of a large fragment of the upper crust, caused by collision of India and Asia, is accommodated by the Ailaoshan-Red River and Xianshuihe-Xiaojiang strike-slip fault systems in the eastern Tibetan Plateau (Fig 1.1a). This probably contributed to the surface uplift and crustal thickening in the eastern Tibetan Plateau since 10-15 Ma (Clark et al., 2005; Royden et al., 2008). The lateral and vertical movement, interacting with the erosion and climate change, have determined the development of the river systems in the eastern Tibetan Plateau.

The uplift of the Tibetan Plateau and building of the Himalaya caused intensification of silicate weathering and organic carbon burial, which account for the lowering of atmospheric CO2 necessary to force global cooling (Dupont-Nivet et al., 2008; Garzione, 2008; Jagoutz et al., 2016). The global climate gradually cooled down from Late Paleocene Thermal Maximum (56 Ma) to cold circumstances with polar ice caps on both poles around late Miocene (Flower and Kennett, 1994). The stepwise increase in elevation during the Himalaya-Tibetan plateau uplift led to a strengthening of the South and East Asia monsoon (Molnar et al., 2010). The arid zone retreated to the Asian interior due to the monsoon intensification around 9-8 Ma (An et al., 2001).
Rivers, draining the Tibetan Plateau, play an important role in changes in climate and topography by transporting large quantities of detritus (Ca and Mg silicate minerals and organic carbon debris) to the ocean. The ongoing development of topography resulting from the collision of India and Asia has caused a remarkable reorganization of the original river patterns. For example, the Yarlung-Tsangpo River first follows the strike of the South Tibetan mountain ranges for 1500 km, and finally cuts across the main ranges of the Himalayas in the Eastern Syntaxis to exit the mountain ranges in Assam, India, as the Brahmaputra River on its way to the delta in Bangladesh. Similarly, fluvial incision, competing with internal tectonic forces in the eastern periphery of the Tibetan Plateau, has also influenced the topography of the Tibetan Plateau in the upper reaches of the Red River, Mekong, and Yangtze (Fig 1.1a). These remarkable river drainage patterns can only be understood from the interplay of tectonism, exhumation and river incision over tens of millions of years as uplift of the Himalayas and the Tibetan Plateau progressed.

The Yangtze River is the largest river in Asia with a length of 6300km. The Yangtze River originates west of the Geladandong Mountain on the Tibetan Plateau and flows southward through deep mountain valleys on the eastern Tibetan Plateau to cut across eastwards towards the Sichuan Basin (Fig 1.1b). From the eastern Sichuan Basin, the Yangtze River incises the Three Gorges valley into the Jianghan Basin and finally flows into the East China Sea. The Yangtze is commonly divided into three sections: the upper, middle and lower reaches. The upper Yangtze is defined from the headwaters to the city of Yichang; the middle reaches traverse from Yichang to Hukou and the lower reaches from Hukou to the East China Sea.

Several lines of evidence support the hypothesis that the major tributaries of upper Yangtze (Dadu, Yalong, Jinsha and Jialing rivers) in the eastern Tibetan Plateau originally flowed southward like the Mekong and Salween into the Red River before the Miocene (Clark et al., 2004; Clift et al., 2006a; Clift et al., 2008). Due to the uplift of the eastern Tibetan Plateau, these rivers changed course and became connected to the middle-lower reaches of the Yangtze River. Although the exact timing of head water capture and thus the “birth” of the Yangtze River as the longest river of Asia has been studied already for almost one century (Clark et al., 2004; Clift et al., 2008; Willis et al., 1906; Wissink et al., 2016), no consensus exists on the exact timing of the final formation of the Yangtze as the river we know today.

The incision event that formed the river channel through the Three Gorges in the middle reaches, and the formation of the “First Bend” in the upper reaches and thereby effectively capturing the upper reaches of the Red River are widely accepted as the two key events that led to the formation of the modern Yangtze River. The formation of the Three Gorges channel in the Wushan Ranges along the east side of the Sichuan Basin makes the connection between the upper reaches in the Sichuan Basin and the middle reaches in the plains of eastern central China. The Jinsha River (main stream of the upper Yangtze) flows southward through a deep mountain valley and makes an abrupt turn northward at Shigu town forming so-called the “First Bend” (Fig 1.1b). The upper Jinsha River (upstream from the Shigu town) originally flowed southward into the Red River and was captured by the mid-lower Yangtze River. This event is regarded as the other critical event in the formation of the modern Yangtze river geometry (Clark et al., 2004; Zheng et al., 2013). Because various methods were used for a range of samples collected in different places yielding different results, there is no consensus yet on the timing of these events. Previous
studies suggest that formation of the Yangtze River can be dated back to either the Eocene-Miocene (Clift et al., 2006a; Hoang et al., 2009; Wissink et al.; Zheng et al., 2013), Pliocene (Fan et al., 2005; Shao et al., 2012) or middle-late Pleistocene (Gu et al., 2014; Yang et al., 2006).

1.2 Aim of study

In order to constrain the development of the Yangtze River, it is crucial to constrain the main capture events (i.e. capture of paleo-rivers to be included to form the modern day Yangtze) in terms of drainage reorganization in different sections of the Yangtze River and the timing of these events. Because the reorganization of river systems is often accompanied by remarkable spatial and temporal variations in sediment provenance, the sediments in the various sedimentary basins along the current path of the Yangtze store the information of its development. In my thesis, the aim is to identify the changes in sediment provenance in space and time with the objective to unravel the formation history of the Yangtze.

I thereby focus on 1) the Jianghan Basin located immediately downstream of the Three Gorges in the middle reaches (Fig 1.1b, Chapter 4), 2) Yangtze gravel sediments distributed on both banks of the river from the Three Gorges area to the delta (orange areas in Fig 1.1b, Chapter 5), and 3) the Jianchuan and Yuanmou basins in upper reaches (white rectangular box in Fig 1.1b, Chapter 6). The Yangtze River flows across the Jianghan Basin from west to east and has deposited a large amount of sediment (Fig 1.1b). The sedimentary record deposited in the Cenozoic in the Jianghan Basin could therefore, in principle, be used to constrain the time of formation of the channel through the Three Gorges and to reconstruct the development of the Yangtze River in the upper reaches. The Yangtze gravel sediments, which are Cenozoic sediments distributed along the banks of the Yangtze River in the middle-lower reaches, have long been considered as a critical line of evidence for the Yangtze evolution (Fig 1.1b). The Jianchuan Basin is located more upstream ~200km west of the Yuanmou Basin and ~30km south of the “First Bend” in the upper Yangtze (Fig 1.1b). The Jianchuan and Yuanmou basin are regarded as the paleo-course of resp. the upper Jinsha and Yalong rivers at that time connecting to the Red River (Clark et al., 2004). The Pliocene sediments in these two basins, in theory, record useful information about the evolution of the upper Yangtze River and its switch from flowing south to east.

1.3 Approach used in this thesis

Single-grain techniques (such as geochronology, isotopic fingerprinting and mineral geochemistry) are particularly important tools for sediment provenance studies. Multiple-proxy, rather than one single-proxy, approaches provide more reliable information on sediment provenance, especially by identification of non-unique and spurious sources. In this study, detrital muscovite and biotite $^{40}\text{Ar}/^{39}\text{Ar}$ dating, detrital zircon U-Pb geochronology and muscovite geochemistry were used to constrain the sediment provenance of Neogene and modern river sediments in the Yangtze River. A minimum of at least two of these provenance tools were used to identify sediment sources in the Yangtze
Figure 1.1 a) Topography of Asia, showing the distribution of the large rivers. The white arrows indicate present-day motion of India, central Tibet and southeast Tibet. The red lines represent faults. The gray and black arrows represent direction of winter and summer monsoon, respectively. XXF - Xianshuihe-Xiaojiang Fault, ARF - Ailaoshan-Red River Fault, LMSF - Longmenshan Fault, SB - Sichuan Basin, JHB - Jianghan Basin, TG - Three Gorges, FB - First Bend. b) A schematic map showing the Yangtze drainage basin. The shaded areas are locations of the Jianchuan and Yuanmou basins, respectively. The orange areas indicate the distribution of the Yangtze gravel sediments. JCB – Jianchuan Basin, YMB – Yuanmou Basin, GM – Geladandong Mountain.
River basin as described in the main chapters of this thesis. In addition to chemical data and age constraints we also measured flow directions based on the orientation of a-axes (the trend of the longest axis) of cobbles found in late Neogene sediments of the Yuanmou basin in chapter 6.

Zircon U-Pb ages record long-term magmatic and high grade metamorphic histories because of its physical robustness and high closure temperature (>900 °C, (Lee et al., 1997)). The detrital zircon U-Pb age distributions provide accurate and useful information about the source area. Zircon (60-125µm) grains are expected to be transported as bed load in the river system due to their high density (4.65 g/cm3) and need ~5-10 ka to travel from source to the delta in the Yangtze River (He et al., 2014 and references therein). Muscovite and biotite have more limited resistance to physical abrasion and chemical weathering when compared to zircon, and thus may reveal information about more recent tectonic events in their source area due to their lower closure temperatures (350 - 425 °C and 300 - 350 °C , respectively (Harrison et al., 2009; McDougall and Harrison, 1999) ). \( {^{40}\text{Ar}/^{39}\text{Ar}} \) ages of muscovite and biotite record the cooling age through the respective mineral closure temperatures of the terrain they originate from. Both muscovite and biotite are less likely to survive multiple erosion and sedimentation cycles, when compared with for example zircon. \( {^{40}\text{Ar}/^{39}\text{Ar}} \) ages of muscovite and biotite have been successfully exploited as provenance tool in many studies (Clift et al., 2004; Clift et al., 2006b; Haines et al., 2004; Hoang et al., 2010; Najman et al., 1997; Pierce et al., 2014). Although the density of muscovite (2.82 g/cm3) and biotite (3.09 g/cm3) is less than zircon (4.65 g/cm3), medium sized (200-500µm) muscovite and biotite grains also transported as bed load or not far above bed load in the Yangtze River (Sun et al., 2016 and references therein). The medium sized muscovite and biotite would require a long time (>1000 years) to travel from source to delta. Generally, igneous muscovite contains more Ti, Al and Na, and less Mg, Si and Fe than metamorphic muscovite (Speer, 1984). The Si, Fe, Mg and Al content of muscovite in metamorphic rocks is variable according the Tschermark substitution (Mg2++Fe2+) [VI]+Si4+[IV]=Al3+[IV]+Al3+[VI] (Massonne and Szpurka, 1997). We therefore use the chemical composition of these elements in muscovite to place constraints on sediment provenance in this study.

This thesis includes 49 samples collected from the Jianghan, Yuanmou and Jianchuan basins and major tributaries or mainstream in the Yangtze River basin. Detrital muscovite, biotite and zircon grains were separated from these samples using standard heavy liquid and magnetic methods. We used standard statistical technique called the Probability Density Plot (PDP) and Kernel Density Estimation (KDE) to plot muscovite and biotite \( {^{40}\text{Ar}/^{39}\text{Ar}} \) ages and zircon U-Pb ages through a Java-based Density Plotter program (Vermeesch, 2012).

The full dataset of this study comprises of 2050 muscovite and 844 biotite \( {^{40}\text{Ar}/^{39}\text{Ar}} \) ages, 1994 zircon U-Pb ages and 928 EMP analyses. It is difficult, if not impossible, to make geological sense of such 'Big Data' sets (sensu Vermeesch and Garzanti, 2015) without statistical help. In the chapter 6, we compute a table of Kolmogorov-Smirnov dissimilarities for each of the three datasets (muscovite and biotite \( {^{40}\text{Ar}/^{39}\text{Ar}} \) ages and geochemistry). We then visually approximate these two-dimensional tables as two-dimensional configurations of points by Multidimensional Scaling (MDS; Vermeesch,
2013). These MDS configurations allow a graphical assessment of the salient similarities and differences between the samples for each of the two datasets. In chapters 4 and 5, we also use Multidimensional Scaling as a first layer of simplification for muscovite and biotite $^{40}$Ar/$^{39}$Ar ages, zircon U-Pb ages and Al/(Fe+Mg+Si) in muscovite. In a second layer of simplification, we combine the several dissimilarity measures in a single three-dimensional matrix. Feeding this data structure into a ‘three-way’ MDS algorithm fits the entire dataset with two pieces of graphical output: a 'group configuration' showing the (dis)similarities between the samples, and a scatter plot of 'source weights' for each of the provenance proxies (Vermeesch and Garzanti, 2015). In chapter 3, comparison between the Yangtze delta and various tributaries allow us to identify the source of sediments that are now reaching delta. In chapter 2, detrital muscovite and biotite ages were directly compared with bedrock ages from geological maps in the Eastern Alps to constrain the sediment provenance as a proof of concept. This is relatively easy compared with identification of provenance of samples from the sedimentary basins (chapter 4 - 6) where multiple aged samples are compared with various tributaries. Therefore, the Multidimensional Scaling was not used in chapters 2 and 3.

1.4 Outline of the thesis

In this thesis, detrital mica geochemistry and geochronology are the tools used to unravel the Yangtze River formation history. In Chapter 2 we test the validity of muscovite and biotite $^{40}$Ar/$^{39}$Ar dating as useful proxy to constrain the sediment provenance in a river system. For this purpose, we used well-constrained drainage basins of limited areal extent in the Eastern Alps located in central Europe with respect to geochronological ages of its bedrock. Detrital muscovite and biotite $^{40}$Ar/$^{39}$Ar ages of nineteen river sand samples from the Eastern Alps are directly compared with the bedrock age in the drainage basin. The muscovite and biotite ages of modern river sands are generally consistent with the bedrock ages in the river basin, suggesting that mica geochronology is a useful and powerful tool to identify the sediment provenance.

Chapter 3 presents the muscovite $^{40}$Ar/$^{39}$Ar ages and geochemistry of modern sediments from major tributaries and mainstream of the Yangtze River. Comparison of muscovite age and geochemistry data between tributaries and mainstream allows us to constrain the recent processes of sediment transport in the Yangtze River system. The sediment contribution calculated from muscovite data was compared with that estimated from current sediment load data from gauging stations. The muscovite data from the modern sediment might represent an “old” erosion pattern unaffected by human impact, but the sediment load data instead would indicate a “young” erosion pattern in direct response to human activity in the catchment area as medium grained (200-500µm) muscovite could be transported much slower than suspended sediment load. The medium grained muscovites in the Yangtze River require a long time (>1000 years) to travel from source to delta. This implies that the impact of human settlements indeed impacts erosion and that a change in sediment provenance is almost immediately recorded.

Chapter 4 focuses on samples collected from two cores in the Jianghan Basin in middle reaches of the Yangtze River. The combination of detrital muscovite $^{40}$Ar/$^{39}$Ar ages
and geochemistry and zircon U-Pb ages in combination with stratigraphic age control shows that the Three Gorges must have formed before the late Pliocene (>3.5 Ma). Our new data also suggest that the originally south flowing upper Dadu River was captured by the rivers in the Sichuan Basin somewhere between 2.1 and 1.2 Ma.

Chapter 5 focuses on the spatial and temporal changes in sediment provenance of the “Yangtze gravel” sediments in the mid-lower Yangtze. We used the muscovite and biotite $^{40}$Ar/$^{39}$Ar ages and muscovite geochemistry to identify the source of the “Yangtze gravel” sediments. The combination of these data suggests that the formation of the Three Gorges occurred somewhere between 36.5 Ma and 22.9 Ma. We suggest that the evolution of the Yangtze River is closely linked to variation in topography and intensification of southeastern summer monsoon caused by uplift of the Tibetan Plateau.

Chapter 6 sheds light on sediments in the Jianchuan and Yuanmou basins in the upper Yangtze, eastern Tibetan Plateau. Muscovite and biotite $^{40}$Ar/$^{39}$Ar ages and muscovite geochemistry were used to constrain the sediment provenance. The spatial and temporal changes in sediment provenance suggest that the upper Jinsha River (upstream from Shigu town) lost its connection with the southward flowing Red River at least before the Pliocene. Our results rule out the possibility that this capture event took place at 1.58 Ma as suggested by others. The current stream directions between Shigu and Panzhihua are north, south and east and must have been formed before 1.58 Ma.

In Chapter 7 the results and implications of this study will be summarized.
Chapter 2

A new detrital mica $^{40}$Ar/$^{39}$Ar dating approach for provenance and exhumation of the Eastern Alps

X.L. Sun, L. Gemignani, T.D. van Gerve, J. Braun and J.R. Wijbrans


Abstract

Thermochronology on detrital minerals is used to constrain the lateral variation of the exhumation rate and the sediment provenance of large sectors of an actively deforming mountain belt. Analysis of modern river sands yields an inventory of ages of rocks currently cropping out and eroding in the hinterland of a river drainage basin. So far, only few studies have focused on testing the consistency of the detrital mineral age distributions and the surface bed-rock thermochronology. We present here new detrital $^{40}$Ar/$^{39}$Ar biotite and muscovite age distributions for nineteen modern river sands from rivers draining the Eastern Alps north of the Periadriatic line. The ages, were compared with the in-situ ages for the bedrock in the hinterland from literature. The results represent three main clusters of ages that record the main exhumation pulses in this sector of the Alps. We have applied two numerical methods to the cooling ages to a) quantify the rates of exhumation of the Tauern Window during Paleocene-Miocene period of the Alpine orogeny, b) linearly compute the spatial variability of the present-day exhumation rates of a set of 4 detrital mineral sample drainage basins along the Inn river stream. Our results suggest a 0.17-0.52 mm/yr range in exhumation rates for the Tauern Window since the Miocene. Our data define more inclusive trends in regional mica cooling ages in the source rocks and can be used to assess sediment provenance and drainage basin averaged bedrock exhumation in different sectors of the Eastern Alps.

$^{1}$This chapter is a joint work of Xilin Sun and Lorenzo Gemignani, both contributed equally to this work.
1 Introduction

Topography in orogenic belts is caused by competition of uplift of the rock pile caused by internal tectonic forces and external surface processes, weathering and erosion, both acting to drive exhumation. Exhumation, weathering and erosion are key surface processes that are in competition to moderate the development of the topography. Topography in turn moderates weathering and erosion as it alters atmospheric circulation and regional precipitation patterns. The rate of exhumation can be constrained by thermochronology on detritus in the sediment record in modern rivers, the foreland basin or on minerals obtained from the bedrock as exposed in crystalline cores of mountain belts. Each of these different approaches derive constraints on the exhumation of the Alps focusing on different windows for processes that happened in the past and processes happening today (Garver et al., 1999; Carrapa, 2009; Carrapa et al., 2004; Von Eynatten and Wijbrans, 2003; Wöfler et al., 2016). Records from sedimentary basins of an evolving hinterland provides unique continuous information on the tectonic evolution of a developing orogen. Applications of detrital thermochronology on both retro- and pro-wedge basin sediments have been applied on the western Alps (Carrapa, 2009; Carrapa et al., 2016; Garver et al., 1999; Stuart, 2002), Central Alps (Spiegel et al., 2000; Spiegel et al., 2004; Von Heynatten and Wijbrans, 2003) and Eastern Alps (Kuhlemann et al., 2004).

Rivers in the Alpine domain transport sediment from the high mountains that are deposited in the foreland basins and thus their sediment load contains key information on sediment provenance, on the age range of rocks contributing to the sediment load, and on exhumation in the source area. However, so far, only relatively few studies have focused on the link between foreland basin record and mountain surface processes from Alpine river sediments (Bernet et al., 2009; Bernet et al., 2004; Glotzbach et al., 2011; Reiter et al., 2013).

Isotopic ages of detrital minerals in modern river sands yield constraints on the range of ages that may be found in rocks currently exposed in the source area and thus preserve the record of its exhumation. Thermochronological techniques, such as U-Th/He, FT on apatite and zircons and $^{40}$Ar/$^{39}$Ar dating of micas and microcline, record the time of mineral exhumation from the depth in the mountain range where the ambient temperatures are equal to the closure temperatures to the surface (Reiners and Brandon, 2006) and thus can be used to constrain the basin averaged exhumation rate of a mountain belt. In the present study, we use $^{40}$Ar/$^{39}$Ar dating of muscovite and biotite single crystals using a laser fusion technique. Muscovite and biotite have limited resistance to physical abrasion and chemical weathering and are therefore well suited to reveal information about recent tectonic events in their source area. Due to their range of closure temperatures (350 - 425°C and 300 - 350°C, respectively) (Harrison et al., 2009; McDougall and Harrison, 1999) the muscovite and biotite age signals record cooling and exhumation from mid-crustal levels in the orogen.

In this paper, we investigate how the $^{40}$Ar/$^{39}$Ar dating on detrital mica crystals, muscovite and biotite, from the modern river sediments can be applied to assess the provenance and the present-day and past exhumation of the Eastern Alps. The Alps form a suitable test-case for such an approach as there is a substantial database of ages obtained
from minerals in the crystalline source rocks (i.e. Hunziker et al., 1992; Scharf et al., 2013). In the first part of the paper we compare our new single grain biotite and muscovite ages from modern rivers with the in-situ thermochronology method to constrain the sediment provenance. In the second part of the paper we apply a new numerical approach to three Inn river-trunk catchments and to one of its lateral tributaries to predict the relative present-day exhumation rates of the catchment areas. Finally, the detrital muscovite and biotite cooling ages of five samples collected from three rivers draining the Tauern Window are used to constrain the relatively young (Miocene) exhumation of the Tauern Window.

2 Geological summary of the Eastern Alps

The Alpine orogen is the result of the collision between Adria with the Eurasian plate since the Cretaceous (Frisch et al., 1998; Stampfli et al., 1998). The modern setting of the Eastern Alps is the result of the last, Tertiary, phase of Alpine orogenesis. Prior to this last phase, during the mid-Cretaceous, the convergence of Adria caused subduction of the Penninic units (continental and oceanic nappes) that reached prograde metamorphic conditions and accreted against the European margin forming an accretionary wedge (Dal Piaz et al., 2003). Subsequently, the progress of the tectonic convergence caused over-thrusting, during the Paleogene, of the Austroalpine nappe stack (Europe-vergent belt) north of the Periadriatic line (the Southern-Alps) (Fig 2.1). This phase of the collision process mainly overprinted the basement nappes, as the cover nappes remained in tectonically high and hence colder positions (Frisch and Gawlick, 2003). Stacking of the Austroalpine units during Late Cretaceous oceanic subduction was accompanied by topographic development and erosion, causing the deposition of the Gosau sediments, for example (Dal Piaz et al., 2003; Froitzheim et al., 1994), crustal scale folding, orogen-parallel extension and lateral extrusion processes that led to the exhumation and over-thrusting of the high grade rocks of the Penninic units during early Tertiary (Schmid et al., 2004, 2013; Stampfli et al., 1998). The Alpine overprinting can be found in the metamorphic domes in the Eastern Alps (belong to the Tauern Window) due to exhumation of deeply buried units in the Neogene and in the contact zones of the Oligocene – Miocene Pohorje and Bregalia plutons (Neubauer et al., 1999). The Tauern Window and the Engadin Window have been described as a crustal-scale duplex (Schmid et al., 2013) that formed during the Oligocene compression phase that was overprinted by the gravitational collapse of the Eastern Alps coupled with substantial lateral extrusion toward the east, during the Miocene, along a conjugate system of shear zones (Frisch et al., 1998; Ratschbacher and Frisch, 1991).

Our work is focused in the (N)-verging sector of the Eastern Alps, north of the Periadriatic line where the main tectonic terranes are from the internal to the external side the Austroalpine nappe system (Adriatic passive continental margin), the Penninic metamorphic nappes system and the Helvetic zone that were thrust on top of the Molasse foreland (Fig 2.1). The Austroalpine nappe is made of a pile of sedimentary cover units and basement nappes that underwent Early-mid Cretaceous (Eo-Alpine) metamorphism and over-thrusted the Mesozoic ophiolitic Penninic units that bound the Tauern Window and the Engadin Window (Dal Piaz et al., 2003; Schmid et al., 2008). The Austroalpine nappe complex can be subdivided into three main nappes systems: the Northern Calcareus
Austroalpine (NCA), the Upper Austroalpine basement nappes and the Austroalpine nappe system situated at the southern margin of the European accretionary wedge (Frisch and Gawlick, 2003). The Austroalpine domains consist of pre-Alpine crystalline basement rocks, low-grade Paleozoic blocks and post-Variscan sedimentary sequences (Frisch et al., 1998). The stacking in the Austroalpine nappe complex is classically related to the subduction of the Piedmont-Liguria Ocean during Cretaceous and to the collision, during the Tertiary, with the Penninic basement (Liu et al., 2001; Pfiffner, 2001). The Tauern Window is characterized by high topography and tectonically by an antiformal stack of Penninic Units bounded by Austroalpine basement rocks (Fugenschuh et al., 1985; Liu et al., 2001).

3 Materials and Methods

3.1 Detrital $^{40}\text{Ar}/^{39}\text{Ar}$ analytical method

Nineteen samples of modern river sands were collected from rivers in the Eastern Alps between eastern Switzerland, Liechtenstein, Austria and northeast Slovenia in the southeast of the study area (Table. 2.1 and Fig 2.1). The sampling sites were located at least 1km away from tributary junctions to the main step of the river and any landslide to avoid bias toward one particular source in the main river stream. Approximately 2kg medium grained sand was collected from the top 10 cm sediment at each sampling location from the edge of the active channel.

Biotite and white mica were separated for radio-isotopic $^{40}\text{Ar}/^{39}\text{Ar}$ analysis. Mineral separation was performed using the standard procedure in the mineral separation laboratory at the Vrije Universiteit of Amsterdam. Organic material was removed by density separation. The samples were sieved to obtain 400-200 μm grain size fractions. A Faul vibration table was used to separate the flat micas from the non-flat minerals. Biotite and muscovite were separated from each other by heavy liquid separation ($\rho_{\text{muscovite}}=2.77-2.9$ g cm$^{-3}$, $\rho_{\text{biotite}}=2.9-3.3$ g cm$^{-3}$) and by making use of the higher magnetic susceptibility of biotite in a Franz magnetic separator. Finally, all samples were hand-picked under a binocular microscope to remove any significant weathering variation or inclusions and obtain 200-250 grains of pure muscovite and biotite. Care was taken to avoid any contamination of the samples.

After separation, the samples were wrapped in Al-foil and loaded in 9 mm ID quartz tubes together with the monitor standard Drachenfels sanidine dated at 25.52 ± 0.08 Ma. This value is compatible with the set of (Kuiper et al., 2008; Renne et al., 2010). Samples were irradiated at the Oregon State University TRIGA reactor in the CLICIT facility for 12 hours. Muscovite and biotite ages determinations were conducted at the argon geochronology laboratory of the Vrije Universiteit of Amsterdam. Single muscovite or biotite grains were loaded into a copper disk with 185 holes of 2mm-diameter and 3mm-depth. The copper disk was heated overnight at 150°C in an ultra-high vacuum sample house fitted with a multispectral ZnS externally pumped double vacuum seal window. Single mica was fused under a 25W Synrad CO$_2$ Laser Instrument. The gas was cleaned in a sample purification system by exposure to SAES St707 (Fe-V-Zr alloy), getters and a SAES NP50 getter device fitted with an ST101 C50 cartridge. The Ar isotope spectrum was
**Figure 2.1** Simplified tectonic map of the Eastern Alps modified after (Schmid et al., 2004). The main litho-tectonic units are indicated in the legend together with the major tectonic discontinuities (red lines). The white stars indicate the samples location and the dotted grey lines the major river paths.

**Figure 2.2** Composite Probability Density Plots for the Biotite distributions (continuous line) and for the muscovite (dotted line); The ages are expressed in million years on the x-axis and on the y-axis, we show the relative probability. The number of single grain analysis are indicated for both the target minerals.
Figure 2.3. Tectonic map and in-situ bed rocks ages of the Eastern Alps. The major river network is indicated by the pale blue paths. The samples are indicated by the yellow stars. The square represents the muscovite data, the circle the biotite and they are associated with a color code as explained in the legend. On the side the boxes display the new $^{40}\text{Ar}^{39}\text{Ar}$ plotted as Kernel Density Estimator (KDE) and as histograms with the same color code of the bed-rock ages. The age range from 0 to 500 million of years. The numbers associated with the in-situ cooling ages describe the references of the work as explained in the legend of the map.
analyzed on Hiden HAL 3F Series 1000 Pulse Ion Counting Triple Filter quadrupole mass spectrometer (Schneider et al., 2009).

A system blank was measured before every fifth sample measurement and three blanks and two gas pipette air aliquots were analyzed at the start and the end of the tray measurement respectively. Total system blank levels were approximately $2-6 \times 10^{-17}$ moles for $^{40}$Ar and $0.5-6 \times 10^{-18}$ moles for $^{39}$Ar, $^{38}$Ar and $^{36}$Ar, and $1-2 \times 10^{-17}$ moles for $^{37}$Ar. The data reduction software ArArCALC2.5 was used for data reduction and age calculation (Koppers, 2002). Corrections were applied for $^{37}$Ar and $^{39}$Ar decay following sample irradiation and for procedure blanks.

Table 2.1. Summary of sample number, rivers and locations expressed as longitude and latitude. Minerals indicates the type of target analysis (Ms = muscovite; Bt = biotite).

<table>
<thead>
<tr>
<th>River</th>
<th>Lab-ID</th>
<th>Longitude</th>
<th>Latitude</th>
<th>Minerals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rhein</td>
<td>EA1</td>
<td>9°39′39″</td>
<td>47°26′58″</td>
<td>Ms and Bt</td>
</tr>
<tr>
<td>Rhein</td>
<td>EA2</td>
<td>9°35′53″</td>
<td>47°13′59″</td>
<td>Ms and Bt</td>
</tr>
<tr>
<td>Inn</td>
<td>EA3</td>
<td>10° 4′45″</td>
<td>46°44′52″</td>
<td>Ms and Bt</td>
</tr>
<tr>
<td>Inn</td>
<td>EA4</td>
<td>10° 4′23″</td>
<td>46°44′58″</td>
<td>Ms and Bt</td>
</tr>
<tr>
<td>Inn</td>
<td>EA5</td>
<td>10° 4′45″</td>
<td>46°44′52″</td>
<td>Ms and Bt</td>
</tr>
<tr>
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<td>EA6</td>
<td>10°38′13″</td>
<td>47° 6′49″</td>
<td>Ms and Bt</td>
</tr>
<tr>
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<td>11°27′27″</td>
<td>47° 6′29″</td>
<td>Ms and Bt</td>
</tr>
<tr>
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<td>EA8</td>
<td>11°51′51″</td>
<td>47°20′51″</td>
<td>Ms and Bt</td>
</tr>
<tr>
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<td>EA9</td>
<td>12°21′14″</td>
<td>47°16′18″</td>
<td>Ms and Bt</td>
</tr>
<tr>
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<td>13°11′47″</td>
<td>47°20′21″</td>
<td>Ms and Bt</td>
</tr>
<tr>
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<td>EA11</td>
<td>12°56′21″</td>
<td>47°56′32″</td>
<td>Ms and Bt</td>
</tr>
<tr>
<td>Tiroler</td>
<td>EA12</td>
<td>12°30′19″</td>
<td>47°49′10″</td>
<td>Ms</td>
</tr>
<tr>
<td>Enns</td>
<td>EA13</td>
<td>14° 5′15″</td>
<td>47°30′58″</td>
<td>Ms and Bt</td>
</tr>
<tr>
<td>Mur</td>
<td>EA14</td>
<td>15°13′50″</td>
<td>47°24′6″</td>
<td>Ms and Bt</td>
</tr>
<tr>
<td>Mur</td>
<td>EA15</td>
<td>15°31′27″</td>
<td>46°53′1″</td>
<td>Ms and Bt</td>
</tr>
<tr>
<td>Drau</td>
<td>EA16</td>
<td>15°29′51″</td>
<td>46°32′37″</td>
<td>Ms and Bt</td>
</tr>
<tr>
<td>Raab</td>
<td>EA17</td>
<td>15°45′5″</td>
<td>47° 3′44″</td>
<td>Ms and Bt</td>
</tr>
<tr>
<td>Raab</td>
<td>EA18</td>
<td>16° 9′57″</td>
<td>46°59′52″</td>
<td>Ms</td>
</tr>
<tr>
<td>Leitha</td>
<td>EA19</td>
<td>16°10′13″</td>
<td>47°43′44″</td>
<td>Ms</td>
</tr>
</tbody>
</table>

3.2 Inversion and mixing of the cooling ages distributions

In the study area, the detrital record yielded a consistent picture of the cooling ages in the downstream sediments of the Eastern Alps. In order to assess the spatial variability of the erosion for each exclusive source draining into the basin, we linearly computed the age distributions of three samples along the Inn river and one tributary draining into it. The method takes advantage of linearly inverting the raw binned age data points without involving any thermal calculation. Previous methods where a thermal model was used (i.e. Brewer et al., 2006) tried to compare their data to theoretical density age distributions that
rely on thermal model predictions. The use of the “raw” binned detrital ages, allowed us to avoid any complication or bias that may arise from assumptions about the past geothermal gradient or rock thermal conductivity and heat production, which can lead to unnecessary uncertainty in interpreting data. Due to the simplicity of the basic assumptions our method is, however, highly limited by the number of samples in the punctual age distribution (weather 20, 30 or 100) as each distribution/sample needs to contain a sufficient number of analyses to provide a robust interpretation that can be applied to an entire catchment area.

We then extrapolated three additional information in order to apply the numerical inversion, as is summarized in table 2.2. The “position” refers to the relative location of the sample in the river networks and it is expressed as a progressively increasing (downstream) numerical value. The position is defined by a positive value for samples located in the main river trunk and by a negative value for the samples located in a tributary. The area of the catchment corresponding to each sample has been calculated from a DEM and is expressed in square km.

The parameter \( \alpha \) in Table 2.2 is a semi-quantitative estimate of the concentration of the dated mineral in the surface rocks of the corresponding catchment. Recently, evidence on bias related to so called mineral fertility or concentration (defined as the target mineral abundance in the source rocks) has been explored (Malusà et al., 2016) within the Western Alps. In their work, Malusà et al., (2016) argue that any geological interpretation obtained from detrital in modern and ancient settings can be significantly improved when mineral fertility is properly taken into account. In the method that we propose here we account for this fundamental parameter, although our estimate of it is extracted from the geological map of the Alps (Bigi et al., 1990).

### Table 2.2. Input parameters used for the inversion of the detrital age distributions.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Position</th>
<th>Area (km(^2))</th>
<th>( \alpha ) value</th>
<th>Mineral</th>
</tr>
</thead>
<tbody>
<tr>
<td>EA3</td>
<td>1</td>
<td>1345</td>
<td>0.75</td>
<td>Bt</td>
</tr>
<tr>
<td>EA4</td>
<td>-2</td>
<td>72</td>
<td>0.70</td>
<td>Bt</td>
</tr>
<tr>
<td>EA5</td>
<td>3</td>
<td>1571</td>
<td>0.35</td>
<td>Bt</td>
</tr>
<tr>
<td>EA6</td>
<td>4</td>
<td>2975</td>
<td>0.65</td>
<td>Bt</td>
</tr>
<tr>
<td>EA3</td>
<td>1</td>
<td>1345</td>
<td>0.70</td>
<td>Ms</td>
</tr>
<tr>
<td>EA4</td>
<td>-2</td>
<td>72</td>
<td>0.75</td>
<td>Ms</td>
</tr>
<tr>
<td>EA5</td>
<td>3</td>
<td>1571</td>
<td>0.40</td>
<td>Ms</td>
</tr>
<tr>
<td>EA6</td>
<td>4</td>
<td>2975</td>
<td>0.70</td>
<td>Ms</td>
</tr>
</tbody>
</table>

### 3.3 The Method

At each of \( M \) sites, we build relative distributions to form \( N \) age bins and we call \( k = 1, \ldots, N \) and \( i = 1, \ldots, M \) the relative height of bin \( k \) in distribution \( i \). We divide the region of interest into exclusive contributing areas, for each of the sites. For each Area, we assume that \( \alpha \) is the relative surface rock density of the mineral used to estimate the age distribution and \( \dot{e}_0 \) is the unknown present-day mean exhumation rate.
It follows that the number of grains of age \( k \) coming out of catchment \( i \) is given by:

\[
D^k_i = A_i \alpha_i \epsilon_i C^k_i \tag{1}
\]

where \( C^k_i \) is the unknown relative concentration of grains of age \( k \) in surficial rocks in Area \( i \).

We can write that the predicted height of bin \( k \) in the distribution observed at site \( i \) should be equal to the total number of grains of age bin \( k \) coming from all upstream areas divided by the total number of grains of all ages coming from all upstream areas, i.e.:

\[
H^k_i = \frac{\sum_{j=1}^{i} \rho_j C^k_j}{\sum_{j=1}^{i} \rho_j} \tag{2}
\]

where:

\[
\rho_j = \frac{\alpha_j \epsilon_j A_j}{\alpha_1 \epsilon_1 A_1} \tag{3}
\]

or, in incremental form:

\[
H^k_i - H^k_{i-1} = (C^k_i - H^k_i) \delta_i \tag{4}
\]

where:

\[
\delta_i = \rho_i / \sum_{j=1}^{i-1} \rho_j \tag{5}
\]

From this relationship we see that the relative changes in bin height between two successive sites along the main stream tell us something about the present-day exhumation rate in the intervening catchment. However, if the relative bin height doesn’t change between two successive sites \( (H^k_i = H^k_{i-1}) \), we cannot tell if it is because the exhumation rate in catchment \( i \) is nil \( (\epsilon_j = 0 \rightarrow \rho_j = 0 \rightarrow \delta_i = 0) \), or because the signature of the source in catchment \( i \), i.e. the distribution of ages at the surface, is identical to that of the previous catchment \( (C^k_i = H^k_i = H^k_{i-1}) \).

Using Equation (4), we can obtain the unknown \( C^k_i \) recursively using:

\[
C^k_i = \frac{H^k_i - H^k_{i-1}}{\delta_i} + H^k_i \tag{6}
\]

with

\[
\delta_i = \max_{k=1, \ldots, N} \left( A_i \alpha_i \sum_{j=1}^{i-1} A_j \alpha_j \frac{H^k_i - H^k_{i-1}}{H^k_i - H^k_{i-1}}, \frac{H^k_i - H^k_{i-1}}{1 - H^k_i} \right) \tag{7}
\]

obtained by assuming that (i) the exhumation rate in catchment \( i \) is equal to that of catchment 1 or (ii) that the concentration in catchment \( i \) must be larger than 0 or (iii) smaller than 1, respectively. We can also deduce an exhumation rate (relative to the exhumation rate in the first catchment, \( \epsilon_1 \)) using:

\[
\epsilon_i = \frac{\delta_i}{A_i \alpha_i \sum_{j=1}^{i-1} A_j \alpha_j \epsilon_j} \tag{8}
\]

For the first catchment, i.e. \( i = 1 \), we assume that \( \epsilon_i = 1 \) and \( C^k_1 = H^k_1 \).
Age distributions from tributaries can be included to improve the solution locally, i.e. in the catchment that includes the tributary. Let’s call $A_T, \alpha_T$ and $\varepsilon_T$ the catchment area, the surface rock density and mean exhumation rate of a tributary in the catchment $i$. We know that $C^*_T = H^*_T$, the measured relative heights of bin $k$ in the tributary. We can compute the exhumation rate in the sub-catchment of the tributary, according to:

$$\varepsilon_i = \min_{k=1,N} \left( \varepsilon_i \frac{A_i \alpha_i C_i}{A_T \alpha_T C_T} \frac{A_i \alpha_i \left(1 - C_i^k\right)}{A_T \alpha_T \left(1 - C_T^k\right)} \varepsilon_i \right)$$

which we can use to compute the $C^*_M$, the unknown relative concentration of grains of age $k$ in surficial rocks in Area $i$ exclusive of the tributary, according to:

$$C^*_M = \frac{A_i \alpha_i \varepsilon_i C_i^k - A_T \alpha_T \varepsilon_T C_T^k}{A_i \alpha_i \varepsilon_i - A_T \alpha_T \varepsilon_T}$$

We assess the uncertainty of our estimates of exhumation rate $\varepsilon_i$, and relative concentrations $C_i^k$, by bootstrapping. For this, we simply use the method described above on a large number of sub-samples of the observed distributions constructed by arbitrarily and randomly removing 25% of the observed age estimates. This yields distributions of exhumation rate and relative concentrations that can be used to estimate the uncertainty arising from the finite sample size. These distributions are usually not normal and we use their modal value, rather than their mean, as the most likely estimate of exhumation rate and their standard deviation to represent uncertainty.

4 Results

The analysis of detrital modern samples has produced a remarkably representative fingerprint of the bedrock ages drained into the basin by erosional and tectonic (i.e. exhumation along faults zones) processes as demonstrated by several works over the past decades (Bernet et al., 2004; Brewer et al., 2006a; Garver et al., 1999). Three major exhumation pulses (Varisican, Post-Variscan and Alpine) are recorded for both biotite and muscovite as shown in the composite total age Probability Density Plots (PDP) (Fig 2.2). The relative peaks of muscovite ages are generally higher for the Varisican and Eo-Alpine events compare to biotite that record mostly Alpine Cenozoic exhumation.

We compared the consistency of the detrital signal with existing in-situ bedrock ages (references are shown in Fig 2.3). The contribution of the source to the drainage basins is tracked in the detrital age distribution by an age-related color code (Fig 2.3). The overall detrital mineral ages are plotted together as histograms and Kernel Density Estimator (KDEs) (Vermeesch, 2012). Comparison of the detrital distributions with the in-situ thermochronological data (Fig 2.3) allows to derive multiple pieces of information. The first piece of information comes from the observed cooling-age distributions from the river samples, which give insight on how much a cooling event has imprinted the source surface unit rocks, under the assumption that it is representative of the entire catchment area. The second piece of information comes from the present-day mixing of the signal into the river, which gives insight about the present exhumation/erosion rate and about the importance of its “imprinting” in the regional-scale geology. In this section, we will
describe the river sample cooling age distributions and how they compare to the available in-situ thermochronological data and which additional information they bring to our comprehension of the regional scale tectonics.

Samples from the Rhein EA1 and EA2 sites and from the Inn EA3, EA4, EA5 sites contain minerals that originate in the internal Penninic and Austroalpine basement nappes and Northern Calcareous Austroalpine. The bedrocks ages available for those basins area are varied and range from 400 Ma to ~10 Ma [Handy et al., 1996; Von Eynatten et al., 1996; Challandes et al., 2003; Wiederkehr et al., 2009]. Detrital mineral ages from the Rhein and Inn samples are consistent and homogeneous for the two target minerals, as 70% of the total distributions are in the range 298±2 to 290±2 Ma. Downstream from the Inn river, sample EA6 presents a more scattered distribution with muscovite peaks at ages 80±20 Ma (40%), 300±20 Ma (50%) and 250 Ma. The biotite ages of EA6 concentrate on a peak at 80±20 Ma that includes 70% of the total distribution with the other 30% of measurements showing a broad scattering of older ages (Fig 2. 3).

The Sill (EA7), Ziller (EA8) and the Salzach (EA9 and EA10) samples contain minerals from catchments draining the Upper Penninic and Upper Austroalpine nappes of the Tauern Window. Those samples yield muscovite and biotite grains younger than 50 Ma and are consistent with a major cluster of published in-situ ages around Paleogene ages (Kurz et al., 2008; Liu et al., 2001; Ratschbacher et al., 2004; Scharf et al., 2013; Warren et al., 2012; Zimmermann et al., 1994). Downstream, the Salzach sample (EA11) contains minerals coming from the external Austroalpine units towards the north. This sample displays a bimodal distribution in the biotite age population with two narrow peaks at 40±5 and 300±20 Ma. In the muscovite, the <50 Ma peak is dominant and represent 95 % of the distribution, with one statistically unrepresentative single grain of 300±20 Ma. The sample downstream of the Salzach basin (EA11) contains mostly muscovite and biotite grains that are drained from the Tauern Window.

Sample EA12 from the Tiroler Achen river received minerals from the northern calcareous Austroalpine units; the detrital muscovite ages distribution is made of a narrow peak at 300 Ma. The Enns (EA13) sample was collected in the middle of the northern calcareous Austroalpine unit that is characterised by a range of muscovite bedrocks ages of 300-200 and 100-50 Ma (Liu et al., 2001). This sample yields a heterogeneous set of ages from 450 to 60 Ma in the biotite distribution, whereas, the muscovite ages from the same samples form a 90-60 Ma peak.

The Mur river where samples EA14 and EA15 were collected originates in the metamorphic internal zone of the Penninic nappes (Tauern Window) which has characteristic in-situ ages of 0-50, 100-200 and 200-300 Ma and flows east towards the Upper Austroalpine basements units (Liu et al., 2001; Neubauer et al., 1995; Scharf et al., 2013). Downstream from sample EA14 site located in the Northern calcareous Austroalpine units, the river bents southward and flows across the Upper Autroalpine basement units and Tertiary cover. The Mur detrital age distributions present a narrow peak at 80±20 Ma. The young (Miocene) age signal of the Tauern Window is not found in the distributions observed in the Mur river.

The Drau river (EA16) originates in the Penninic units of the Tauern Window south of the main ranges and drains along a west-to-east section of the internal units of the
Upper Austroalpine basement nappes. Published bedrocks ages are comprised into several intervals, i.e. 50-5 Ma, 100-50 Ma, 300-200 Ma and 400-300 Ma (Ratschbacher et al., 2004; Wiederkehr et al., 2009) for the muscovite and 100-50 Ma for the biotite (Wiederkehr et al., 2009). This wide range of ages is recovered in our detrital muscovite data which display peaks clustering around 80±3 Ma (70 %), 300±2 Ma (10%), 180±2 Ma (5%), 140±2 Ma (5%) and 47 ±10Ma (10%). A minor 10-30 Ma peak, related to the internal metamorphic core of the Tauern Window, is present in the biotite age distribution.

Samples EA17 and EA18 from the Raab river receive mineral grains from the Lower and Upper Austroalpine nappe and Tertiary cover units, that yield mostly pre-Varisican and Varisican age signatures and no Alpine overprinting as observed from several in-situ age analysis (Dallmeyer, R. D., Handler R., Neubauer F., 1998). Our detrital muscovite age distribution shows peaks at 240-310 Ma, 310-300 Ma and 200-80 Ma which is consistent with observed in-situ ages. Sample EA19 (for which we only have a muscovite age distribution) is derived from a location draining the northern calcareous Austroalpine and the Austroalpine basement nappes and present circa 70% of the muscovite ages ranging within 298±2 Ma and 290±2 reflecting an univocal Varisican range of ages.

As described above our detrital basin-related age distributions are generally comparable with the bedrocks ages, although information on in-situ bed rock ages is fragmentary. Interestingly, the most recent Alpine (< 50 Ma) pulse of exhumation and metamorphism is spatially confined to the Tauern Window and Engadin Window and within the catchments draining those units (Fig 2.3). As pointed out earlier, these areas have experienced exhumation since the Oligocene along major thrust zones during episodic lateral (E-W) extension in a convergent (N-S) steady regime (Ratschbacher and Frisch, 1991). In the wester sector of the mountain belt a Quaternary pulse of exhumation has been interpreted as related to the isostatic rebound resulting from glacial erosion (Champagnac et al., 2008; Herman and Champagnac, 2016). The < 50 Ma cooling signal is recorded in the tributaries draining the Tauern Window and is transported downstream in the Salzach river; but is not seen in the catchments of the Mur, Drau and Enns rivers. Those rivers mostly record pre-Alpine and Varisican exhumation of the Austroalpine units. The Varisican signal is pervasive and constitutes the major peak in all basins draining towards the North-west and in the rivers draining the Northern Calcareous Austroalpine units.

5 Discussion

5.1 Application of the mixing model to the Inn river detrital age distributions

Mean present-day exhumation rates, their standard deviation and modal values obtained by the inversion of the age distributions as described above are shown in Table 2.2. The observed age distributions and predicted concentration of surface ages are displayed as normalized histograms in Fig 2.4a and b (from the biotite and muscovite data respectively). Predicted modal exhumation rates together with the relative surface age concentration for the muscovite and biotite are summarized in map form in Fig 2.5. The raw age data are available in the data repository.

The Inn river originates in the pre-Alpine basement of the Grisons-Bernina units.
(Lower Austroalpine) and crosses the Cenozoic Penninic nappes of the Engadin Window in the upper reaches of the river (Figs 2.1 - 2.2). The observed detrital age distributions of this area record mostly Pre-Alpine metamorphism and exhumation (compare gray histogram bars in Fig 2.4). From the inversion of the detrital ages the highest present-day exhumation rates are predicted to occur in the lower part of the main trunk (sample EA6). Interestingly, there is a good correlation between catchments where high concentrations of young surface ages (0-50 Ma and 50-100 Ma) are seen and catchments where higher present-day exhumation rates are predicted by the inversion. Similarly, in the inversion predictions, there is a good correspondence between the predicted lower present-day exhumation rates and the size of older age bins generated by the algorithm (compare central panel displaying the predicted present-day exhumation rate with the upper/lower panels showing the relative age concentrations of Fig 2.5 b-c). The lowest present-day exhumation rates are predicted where the oldest bin of surface age are drained into the system by the lateral tributary near sample site EA4.

![Figure 2.4. Results of the computation of the age distribution. a) Observed surface distributions of ages (light grey) for the samples collected at locations showed in Figure 2.5 (a) and predicted surface age distributions (dark grey) in corresponding catchment areas for the biotite ages and for the muscovite (b).](image)

Looking at the present-day exhumation rate distributions obtained by using the bootstrapping technique (Table 2.3), we can see that the standard deviations are commonly large, i.e. of the order of 35-55 % of the mean predicted exhumation rate for both the muscovite and the biotite age samples. We note also that, for both systems, the modal value is significantly smaller than the mean value where exhumation rate values are highest.

The predicted concentrations of cooling ages also show that there is a peak of younger ages, probably related to the presence of Penninic units (Tauern Window) in the system, that is recorded at the upstream EA3 site and at the downstream EA6 site. This event is
not recorded in neither the lateral tributary site EA4 nor in the flowing catchment site EA5 where older peaks of ages dominate. In summary, the inversion of the binned detrital-age distributions has allowed us to quantitatively constrain the spatial variability of exhumation rates along the Inn river. Using the constraints derived from a lateral tributary entering in the system we have also demonstrated how, locally, the contribution into the system of older (Varisican) surface ages has enabled us to document a marked decrease in present day-exhumation rate estimates.

**Figure 2.5.** Topographic map, catchments area (light gray) and sample locations (red dots) used for the inversion (a). The Inn river and the flowing direction are indicated in by the white arrow. Predicted modal exhumation rates and relative (normalized as that the sum of the 5 bins is 1) concentrations of surface age distributions for the biotite (b) and muscovite (c).
Table 2.3. Computed relative exhumation rates for the two target minerals, standard deviation and modal values obtained from the mixing model and bootstrapping procedure. Locations refer to the sample sites of Figure 2.5.

<table>
<thead>
<tr>
<th>Locations</th>
<th>Mean erosion rate</th>
<th>St. deviation</th>
<th>Modal value</th>
<th>Mineral</th>
</tr>
</thead>
<tbody>
<tr>
<td>EA3</td>
<td>0.957</td>
<td>0.000</td>
<td>0.957</td>
<td>Bt</td>
</tr>
<tr>
<td>EA5</td>
<td>0.561</td>
<td>0.206</td>
<td>0.671</td>
<td>Bt</td>
</tr>
<tr>
<td>EA6</td>
<td>1.481</td>
<td>0.825</td>
<td>1.128</td>
<td>Bt</td>
</tr>
<tr>
<td>EA4</td>
<td>0.488</td>
<td>0.297</td>
<td>0.670</td>
<td>Bt</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Locations</th>
<th>Mean erosion rate</th>
<th>St. deviation</th>
<th>Modal value</th>
<th>Mineral</th>
</tr>
</thead>
<tbody>
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<td>0.410</td>
<td>0.000</td>
<td>0.409</td>
<td>Ms</td>
</tr>
<tr>
<td>EA5</td>
<td>0.213</td>
<td>0.118</td>
<td>0.127</td>
<td>Ms</td>
</tr>
<tr>
<td>EA6</td>
<td>2.376</td>
<td>1.346</td>
<td>1.807</td>
<td>Ms</td>
</tr>
<tr>
<td>EA4</td>
<td>0.208</td>
<td>0.125</td>
<td>0.131</td>
<td>Ms</td>
</tr>
</tbody>
</table>

5.2 Exhumation rates from the Tauern Window

Comparing detrital ages and bedrock ages suggests that almost all young micas (<50 Ma) were derived from the Tauern Window (section 4). These young mica ages are therefore likely to mostly provide information about the exhumation rate of the Tauern Window. The muscovite and biotite $^{40}\text{Ar}/^{39}\text{Ar}$ age record the time taken for each mineral to be exhumed from the depth of its closure temperature to the surface (assuming that the surface transport time, i.e. of the order of thousands of years, is short compared to the time necessary for exhumation, i.e. of the order of millions of years). Consequently, a cooling age can be used to calculate a first-order approximation of the exhumation rate, E, according to:

$$E = \frac{R_{\text{range}}}{t_{\text{range}}} = \frac{(Z_{\text{max}} - Z_{\text{min}})}{(t_{\text{max}} - t_{\text{min}})}$$  \hspace{1cm} (11)

where the $Z_{\text{max}}$ and $Z_{\text{min}}$ are the highest and lowest elevations of one catchment basin, and $t_{\text{max}}$ and $t_{\text{min}}$ are the oldest and youngest ages in a given catchment/sample. We make the simplifying assumption that the difference between highest elevation ($Z_{\text{max}}$) and lowest elevation ($Z_{\text{min}}$) is the main cause for the difference between the oldest ($t_{\text{max}}$) and youngest ($t_{\text{min}}$) ages observed in a given distribution. The youngest (oldest) detrital muscovite or biotite ages in a river sample are expected to originate from the lowest (highest) elevation. This validity of this assumption can evaluated by comparing the hypsometric curve computed in the catchment and the observed cooling age cumulative curve (Fig 2.6). If the two curves are similar, our assumption is valid and we can derived from it an approximate estimation of exhumation rate, E.

Samples EA7 - EA11 were collected from rivers originating in the Tauern Window (Fig 2.6). The detrital muscovite and biotite age distributions of these samples are used to constrain the average exhumation rate of the Tauern Window. Because surface rocks of the Tauern Window form only part of the catchment area of sample EA11 (Fig 2.6), we infer that the muscovite and biotite grains that form the young age peak of this sample were
Based on the detrital age and elevation data, we calculated an approximate value for the exhumation rate for every sample catchment (EA7 - EA11), by using Equation (11). For samples EA9 - EA11 we only uses the young (< 50 Ma) ages to calculate the exhumation rate. We found that the highest erosion rate estimates based on both muscovite and biotite data are from sample EA7 and EA9 with inferred values of 0.52 mm/yr and 0.38 mm/yr, respectively (Fig 2.4). Both samples come from points where the sediment load in the river comes from a relatively small part of the total drainage area covered by the Tauern Window. The hypsometric curve and cooling age cumulative curve of sample EA7 are more similar than in any other sample (Fig 2.6), implying that the exhumation rate obtained for this sample is the most reliable. The lowest exhumation rate is predicted in sample EA11 (0.11-0.12 mm/yr) where the river sediment load is derived from the largest area of all sites. The older mica ages appearing in sample EA11 cause this lower exhumation rate estimate. The exhumation rate based on muscovite and biotite in samples EA7 and EA9 are significantly different, which may be caused by the limited number of grains and thus $^{40}$Ar/$^{39}$Ar ages in these samples. Because the catchment of samples EA7 - EA9 are smaller than those of EA10 - EA11, the corresponding estimates of exhumation
rates are likely to be more reliable. Our data and its interpretation therefore suggest that the exhumation rate of the Tauern Window is comprised between 0.17 and 0.52 mm/yr. The muscovite and biotite ages record an average exhumation rate for the Miocene. Several lines of evidence suggest that the erosion rate significantly increased over the past 5 Ma in the Tauern Window to reach values as high as 1 mm/yr as a result of the general cooling of northern hemisphere climate and the onset of periodic glaciation causing enhanced erosion of mountainous regions (Champagnac et al., 2007; Herman and Champagnac, 2016). This may explain why the average Miocene exhumation rate deduced from our data is lower than the Pliocene exhumation rate calculated by other methods.

6 Conclusions

We have demonstrated here that using detrital age data obtained from modern river sands in the Eastern Alps, we were able to derive first-order information on the spatial variability in exhumation rate averaged over large segments of the mountain belt. We also predicted the distribution of in-situ bedrock ages exposed in each drainage basin that was assessed. The age distributions were compared with known distributions of ages published for bedrock outcrops, and used to refine the existing information on the relative contribution of different units to the erosion and consequently to river sediment load. Three main exhumation pulses, classically described within the Alps as Varisican (350-300 Ma), Pre-Alpine (150-50 Ma) and Alpine (50-5 Ma) are clearly recorded in our dataset. We show that the Cenozoic Alpine metamorphism and exhumation are confined to the Penninic units of the Tauern and Engadin Windows and that the resulting thermochronological signal is transported towards the north by the rivers network into the foreland basin.

Linear inversion of mineral age distributions along the Inn river showed that steady low erosion rates characterise the catchments that drain the Austroalpine units (EA3, EA4, EA5) for both target minerals. A two-fold increase in erosion rate is recorded in the downstream EA6 sample where a clear input of younger surface ages from the Penninic units of the Tauern Window and Engadin Window are added to the signal derived from erosion of Austroalpine units.

Based on the muscovite and biotite age distributions derived from the Tauern Window, we conclude that the highest computed exhumation rates (0.52 mm/yr) are observed in the eastern sector of the Tauern Window (sample EA7 from the Sill River). The lowest estimated exhumation rate estimates (0.11mm/yr) are found in the eastern parts of the Tauern Window (EA11). We demonstrated that both dataset should yield reliable estimates of exhumation rate that are also compatible with previous studies suggesting high exhumation rate values from the Tauern Window between 15-20 Ma and relatively lower but constant values since then, at least until 4-2 Ma (Fox et al., 2016). The middle-Miocene pulse of exhumation which caused these differences in recent exhumation rate has been interpreted as resulting from tectonic escape and convergence related to the lateral extrusion of the Eastern Alps (Wölfler et al., 2016). Our data suggest an increase in exhumation rates in the western parts of the Tauern Window.

This work also demonstrate the strength of single grain Ar-dating of detrital mica minerals, to constrain the past and present exhumation history of a given tectonic
area, from the analysis of modern detritus, in addition to deriving a reliable picture of the contributing sources as previously done (Bernet et al., 2001; Brewer et al., 2006b; Carrapa et al., 2004). We also demonstrate that modern river catchment-related thermochronology is sufficiently precise to characterize the tectonic history of middle to high grade rocks within an actively deforming mountain orogen. However, further improvements are needed to precisely unravel the dynamic of transport and comminution of the target minerals from the source to the basin and the bias that could result from differences in so called mineral fertility within the source rocks.
Chapter 3

Human impact on erosion patterns and sediment transport in the Yangtze River

Xilin Sun, Chang’an Li, K.F. Kuiper, Zengjie Zhang, Jianhua Gao, J.R. Wijbrans


Abstract

Sediment load in rivers is an indicator of erosional processes in the upstream river catchments. Understanding the origin and composition of the sediment load can help to assess the influence of natural processes and human activities on erosion. Tectonic uplift, precipitation and run-off, hill slopes and vegetation can influence erosion in natural systems. Agriculture and deforestation are expected to increase the sediment yield, but dams and reservoirs can trap much of this sediment before it reaches the ocean. Here, we use major element composition and \(^{40}\text{Ar}/^{39}\text{Ar}\) ages of detrital muscovites to constrain the sediment contribution of various tributaries to sedimentation in the Yangtze delta. The sediment contribution calculated from muscovite data was compared with that estimated from current sediment load data from gauging stations. Muscovite data show that the main contributor to the Yangtze delta sands is the Min River, while the current sediment load suggest that the Jinsha and Jialing rivers are the most important current contributors to delta sediments. We suggest that this difference reflects an “old” and “young” erosion pattern, respectively as medium grained muscovite could be transported much slower than suspended sediment load in the complex river-lake systems of the Yangtze River basin. These two different erosion patterns likely reflect enhanced human activity (deforestation, cultivation, and mining) that increasingly overwhelmed long-time natural factors controls on erosion since ~1900 cal yr B.P.
1 Introduction

Erosion patterns are generally controlled by the interaction of a number of processes in natural systems, including precipitation, run-off, active tectonic processes, hillslope steepness and vegetation (Anders et al., 2008; Roering et al., 2007). However, it is recognized that human activities can significantly change the erosion patterns and rates (Bayon et al., 2012; He et al., 2014; Hu et al., 2013; Reusser et al., 2015; Wan et al., 2015). Human activities such as agriculture and deforestation can dramatically increase the sediment yield (Hooke, 2000), while dam constructions can slow down sediment transport to the oceans (Yang et al., 2011). Understanding “old” erosion patterns before the impact of human activities is critical for constraining human societal influence on erosion patterns.

The Yangtze is a suitable place to examine changes in erosion patterns caused by human activities. The Yangtze River is the largest river (6300 km long) at the periphery of the Tibetan Plateau and historically fourth largest in the world in terms of sediment discharge before dam constructions; 480 million tons per year (Wang et al., 2011). More than 400 million people - 6.6% of the world’s population - are living in its catchment. Widespread settlement sites found in the Yangtze basin date back to five thousand years ago (Wu et al., 2012). The western part of the Yangtze River basin covers much of the eastern Tibetan plateau. Tectonic activity, steep topography, strong precipitation and low evaporation and therefore high run-off on the edges of the eastern Tibetan plateau are expected to drive fast erosion in this area (Godard et al., 2010; Liu-Zeng et al., 2011; Ouimet et al., 2010). Pollen records and sediment volume in prograding deltaic sediments over the past 6000 years suggest that the natural erosion rates were significantly disturbed by human activities (Saito et al., 2001; Yi et al., 2003). Detrital U-Pb zircon data suggest that the disturbance of the landscape by human settlement enhanced sediment production after ~5000 BC in the Yangtze River basin (He et al., 2014). However, the amount of studies about human impact on erosion patterns in the Yangtze River basin is limited.

In this study, we use the $^{40}\text{Ar}/^{39}\text{Ar}$ age distribution of detrital muscovite to determine the erosion and sediment transport processes of the Yangtze River system and to delineate the spatial pattern of erosion in the Yangtze River drainage basin. Because muscovite has a lower hardness and closure temperature (350 - 450°C, Haines et al. (2004)) compared to zircon (>900 °C, Lee et al. (1997)), it is less likely to survive multiple orogenic erosion-depositional cycles compared to zircon and may contain, therefore, more information on the most recent orogenic uplift and erosion patterns of the eastern Tibet Plateau. In recent years, the $^{40}\text{Ar}/^{39}\text{Ar}$ dating of detrital muscovite from ancient and modern sediments has proven to be a useful tool for reconstructing exhumation histories and sedimentary processes (Clift et al., 2006; Hoang et al., 2010; Najman et al., 1997). The ages of detrital muscovite grains from modern sediments in the delta and headwater of the Yangtze River are dated by Hoang et al. (2010). We combine these ages with new $^{40}\text{Ar}/^{39}\text{Ar}$ data for modern sediments from the Yangtze River basin. Our approach characterizes the muscovite age distribution along different segments of the Yangtze River.

The transport time of medium sized muscovite grains (200-500 µm) from the headwaters to the delta can be long (millennial timescales) because these muscovite grains are expected to be transported as bed load in the complex river-lake systems of the Yangtze.
River basin (Wei et al., 1986). Thus these medium sized muscovite grains are expected to record the “old” erosion patterns (millennial) of the Yangtze River basin. Modern erosion patterns can be constrained by the modern suspended sediment load data and compared with the muscovite data in the delta that represent older erosional processes. Comparison of these datasets can therefore shed light on the impact of humans on erosion.

2 The Yangtze River system

The Yangtze River catchment area covers a total area of $181 \times 10^4 \text{ km}^2$ and the Yangtze River is the third longest river in the world. The Yangtze River can be divided into three catchment areas: (1) the upstream Yangtze covers its headstream to Yichang; (2) the middle Yangtze traverses from Yichang to Hukou; (3) and the lower Yangtze passes through Hukou and the delta (Fig 3.1). The Yangtze River originates west of the Geladandong Mountain (highest altitude: 6621m) on the Tibetan Plateau and flows into the East China Sea. On the eastern Tibetan Plateau, the river flows southward through deep mountain valleys and makes abrupt turns northwards and southwards from Shigu (Fig 3.1). The river flows west to east through the Sichuan Basin and cuts through the Three Gorges region before descending into the Jianghan Basin. From the Three Gorges region the Yangtze River travels through a complex system of lakes and multiple river channels developed on the plains before reaching the delta.

3 Sampling and analytical methods

3.1 Sample description

In total, ten river sand samples were collected from three locations along the main Yangtze River and seven major tributaries (Fig 3.1). Sample information is given in Table 3.1. Collection of ten modern sediments was conducted in October 2012 following the summer monsoon season. This time period was selected because the sediment we collected was newly-deposited sediment due to high precipitation and high discharge during the summer monsoon season. High precipitation during summer should have caused intense erosion and maximum delivery of bedrock muscovite populations into the Yangtze River system. Approximately 2kg medium grained sand was collected from the top 10 cm sediment at each sampling location from the edge of the active channel. We chose our sampling sites at least 2km away from small tributaries and any landslides to avoid bias toward one particular source.

3.2 Analytical methods

Detrital muscovite grains (200-500 µm) were separated from samples using standard mineral separation techniques and handpicked under a microscope. The muscovite was randomly split into two aliquots, one used for chemical analyses and another used to determine $^{40}\text{Ar}/^{39}\text{Ar}$ ages. The muscovite grains from the first aliquot were mounted on a double-sided tape, cast in epoxy resin, and polished to expose surfaces for electron microprobe analysis. The chemical composition of the muscovite grains were measured by JEOL JX-A8800M electron microprobe at VU University Amsterdam. Wavelength dispersive spectrometers were used with 20nA beam current and 15 kV accelerating voltage.
Sample CJ7 was analyzed at Peking University in Beijing, China. This sample was irradiated in the 49-2 Nuclear Reactor for 24h at the China Institute of Atomic Energy. The in-house standard mineral Zhoukoudian biotite (ZBH-25, Age: 132.7 Ma) (Sang et al.,

Figure 3.1. A schematic map showing the drainage basin, sampling locations and main distributaries of the Yangtze River. Sample locations are shown as filled circles. The yellow stars represent sample sites by Hoang et al. (2010).
was used to measure neutron flux variation (J). Single muscovite was put into 2 mm diameter wells in a copper disk and fused under New Wave Research CO$_2$ Laser Instrument connected to GV 5400 Noble Gas MS at Peking University. The released gas was cleaned for four minutes with two Al-Zr getters. Blank levels were approximately $3.9 \times 10^{-16}$ mol at $^{40}$Ar and $1.5 \times 10^{-17}$ mol at $^{36}$Ar. Blanks were run every three analyses. Analytical details are further described in Zhu et al. (2007). The MASS SPEC (V.7.84) programs from the Berkeley Geochronology Center were used for data reduction.

Table 3.1 Summary of sample numbers and sample locations.

<table>
<thead>
<tr>
<th>Type</th>
<th>Number</th>
<th>Rivers</th>
<th>Longitude</th>
<th>Latitude</th>
<th>Locations</th>
<th>Data source</th>
</tr>
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<tr>
<td>Tributary</td>
<td>CJ1</td>
<td>Yalong</td>
<td>101°48′01″</td>
<td>26°36′29″</td>
<td>Panzhihua</td>
<td>This study</td>
</tr>
<tr>
<td></td>
<td>CJ3</td>
<td>Min</td>
<td>104°33′46″</td>
<td>28°48′26″</td>
<td>Yibin</td>
<td>This study</td>
</tr>
<tr>
<td></td>
<td>CJ4</td>
<td>Jialing</td>
<td>106°23′49″</td>
<td>29°53′13″</td>
<td>Beibei</td>
<td>This study</td>
</tr>
<tr>
<td></td>
<td>CJ5</td>
<td>Han</td>
<td>112°33′30″</td>
<td>31°11′09″</td>
<td>Zhongxiang</td>
<td>This study</td>
</tr>
<tr>
<td></td>
<td>CJ6</td>
<td>Xiang</td>
<td>112°55′19″</td>
<td>28°03′10″</td>
<td>Changsha</td>
<td>This study</td>
</tr>
<tr>
<td></td>
<td>CJ8</td>
<td>Gan</td>
<td>115°51′21″</td>
<td>28°40′50″</td>
<td>Nanchang</td>
<td>This study</td>
</tr>
<tr>
<td></td>
<td>CJ9</td>
<td>Zi</td>
<td>112°18′13″</td>
<td>28°36′54″</td>
<td>Yiyang</td>
<td>This study</td>
</tr>
<tr>
<td>Mainstream</td>
<td>CJ0</td>
<td>upper Jinsha</td>
<td>99°57′23″</td>
<td>26°58′09″</td>
<td>Shigu</td>
<td>This study</td>
</tr>
<tr>
<td></td>
<td>CJ2</td>
<td>lower Jinsha</td>
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<td>28°45′04″</td>
<td>Yibin</td>
<td>This study</td>
</tr>
<tr>
<td></td>
<td>CJ7</td>
<td>Yangtze</td>
<td>111°27′02″</td>
<td>30°27′39″</td>
<td>Yichang</td>
<td>This study</td>
</tr>
</tbody>
</table>

40529yu03 upper Jinsha | 99°57′87″ | 26°52′14″ | Shigu | Hoang et al. (2010) |

Xing-1 Yangtze | 121°30′08″ | 31°19′35″ | Delta | Hoang et al. (2010) |

Note: We collected sample CJ0 from Shigu near sample 40529yu03 in Hoang et al. (2010) and analyzed the chemical compositions of muscovite grains from this sample. Here we use $^{40}$Ar/$^{39}$Ar muscovite ages from sample 40529yu03 and muscovite geochemistry from sample CJ0 to represent the upper Jinsha River.

4 Results

4.1 Microprobe analysis

Eight modern sediments from the Yangtze River were analyzed to assess the compositional variability in the detrital grains (Fig 3.2). Fig 3.2 shows all relevant data from our samples. Generally, igneous muscovite contains more Al and less Si and Fe than muscovite of metamorphic origin. The Si, Al and Fe contents of muscovite in metamorphic rocks are variable according to Tschermak’s substitution $(\text{Mg}+\text{Fe}^{2+})_6^6+\text{Si}^{4-}=[\text{Al}^{4+}]+\text{Al}^{6+}$ (Massonne and Szpurka, 1997). Therefore, the muscovite composition (i.e., Al, Fe and Si) can be used to unravel an igneous and/or metamorphic source from major tributaries to the main stream at Yibin and Yichang.

The chemical compositions of muscovite grains from the Shigu (CJ0) and Yalong River (CJ1) were compared to those from the mainstream at Yibin (CJ2). The detrital muscovite grains from Shigu have a slight overlap with data points of the Yibin sample (CJ2) (Fig 3.2a & b). Muscovite grains from the Yalong River display low Fe and Si and high Al contents with unimodal distribution (Fig 3.2a & b). The mainstream grains from Yibin form two distinct groups, reflecting that they were derived from different source
regions. However, only 3 of 20 muscovite grains analyzed overlap with those of the Yalong River. About 50% of data points of the Yibin sample do not overlap with those from the Yalong River and Shigu (Fig 3.2a & b). Muscovite grains from Yichang (CJ7) (Fig 3.2c & d) display a low to high Si content with polymodal distributions, suggesting that they originate from more complex source regions. Thirteen of twenty grains from Yichang (CJ7) have chemical compositions similar to those of the Min River. Two of twenty grains analyzed fall within the Jinsha River field (CJ2) (Fig 3.2c & d).

4.2 $^{40}$Ar/$^{39}$Ar single-grain dating

In total 377 muscovite single crystal $^{40}$Ar/$^{39}$Ar ages were obtained from river sand samples collected in this study (Table 3.1). The results of the Shigu and Yangtze delta from previous work by Hoang et al. (2010) are also summarized here for comparison (Fig 3.3a & k).

**Figure 3.2a-d** Plots of electron microprobe analysis of muscovite grains from the Yangtze sediments, (a) and (b) show Si versus Fe and Si versus Al contents (in atomic formula units, p.f.u., calculated on 11 oxygens) from the western part of the upper Yangtze River. (c) and (d) show Si versus Fe and Si versus Al contents from the eastern part of the upper Yangtze River.
4.2.1 Samples from the main stream

Samples 40529yu03 and Xing-1 (Fig 3.1) collected from Shigu (most upstream sample) and the Yangtze delta (most downstream sample) were dated by Hoang et al., (2010). The Shigu sample age population shows a well-defined age peak around 240 Ma (Fig 3.3a).

Sample CJ2 was from the main stream near Yibin before the Min River’s intersection with the Yangtze River. About 25% of the total dated muscovite grains is younger than 300 Ma, and dominated by an age peak at ~252 Ma (Fig 3.3c). About 61% of the dated muscovite grains show a continuous distribution between 360 Ma and 750 Ma.

Sample CJ7 (Fig 3.1) was collected from the mainstream near Yichang. Sixty-one analyses of individual grains show a considerable spread of muscovite ages ranging from 12 to 805 Ma with five main age modes occurring at <173, 209-258, 330-350, 390-450, and 805 Ma in the probability density plot (Fig 3.3f).

4.2.2 Samples from tributaries

Forty analyses were conducted for the sample (CJ1) from the Yalong River in the upper Yangtze. About 83% of the muscovite grains is older than 500 Ma with a peak around 700-870 Ma (Fig 3.3b). The remaining ages can be predominantly grouped at 230-290 Ma representing ~13% of the total dated grains.

All 40Ar/39Ar single-grain muscovite data from the Min River are younger than 150 Ma, with age peaks around ~6 Ma and ~37 Ma (Fig 3.3d.). The highest concentration (~73%; n=30) of muscovite in the Min River is distributed between 30-85 Ma with a ~37 Ma peak. From all sampled tributaries only the Min River has muscovite grains younger than 80 Ma except two grains in the Shigu (40529yu03) and Yibin (CJ2) samples.

The muscovite apparent ages of 37 detrital grains from the Jialing River show a wide range from 190 Ma to 1850 Ma. It yields ~76% muscovite ages between 190 Ma and 260 Ma, with a prominent peak at ~208 Ma (Fig 3.3e). For older muscovite, 5 of 37(~14%) muscovite grains distributed between 1000 Ma and 2000 Ma.

The sample from the Han River is dominated by muscovite ages between 165 Ma and 205 Ma, with a major peak around 188 Ma (n=12) and a minor peak at 173 Ma (n=9) (Fig 3.3g). Muscovite ages of 165-205 Ma account for ~76% of total dated grains. Muscovite ages of 320-360 Ma account for ~16% of total dated grains.

The sample CJ6 was collected from the Xiang River. The muscovite ages are dominated by clusters at 80-100 Ma, 110-130 Ma and 200-240 Ma, accounting for ~15%, ~20% and ~43%, respectively, of the total dated grains (Fig 3.3i).

Sample CJ8 was collected from the Gan River in the lower reaches. This sample is dominated by age clusters at 130-160 Ma (~33%), 180-267 Ma (~46%) and 315-400 Ma (~18%) (Fig 3.3j).

Sample CJ9 was collected from the Zi River in the middle reaches of the Yangtze. Twenty-seven muscovite grains show dominant population of 200-235 Ma (peak age ~220 Ma) and minor population of ~98 Ma and ~270 Ma (Fig 3.3h).
Figure 3.3 Probability density diagrams for $^{40}$Ar/$^{39}$Ar ages of detrital muscovite grains within Yangtze River basin. The Shigu and the Yangtze delta data are from Hoang et al. (2010).
5 Discussion

5.1 Provenance of the modern Yangtze River

Comparison of detrital muscovite ages of three samples from the main stream (Yibin, Yichang and Yangtze Delta) with samples from the various tributaries allow us to constrain the potential source areas of muscovite in the modern river sediments. We analyzed 30-40 grains from the samples of the major tributaries and ~60 grains from the mainstream samples. Estimates of the number of grains that should be analyzed to reliably determine the source area of sediments in large rivers, range from ~60 (Dodson et al., 1988) to 117 grains (Vermeesch, 2004). The latter should guarantee that 95% of the populations are indeed detected (at 95% confidence level) assuming a complex age distribution (>20 age fractions). If a sample population represents a more simple distribution the number of analyses can be decreased. Because most of samples from tributaries have relatively simple age distributions (<20 fractions, Fig 3.3), we analyzed 30-40 grains from the samples of the major tributaries. Because we analyzed ~60 grains from the mainstream samples, 90% of the populations are not missed assuming 20 age fractions and 98% confidence level (Vermeesch, 2004). Since the aim of the present study is to investigate the major sediment sources and not the exact provenance of the minor components, our number of analyses is justified.

5.1.1 “Western part of Upper Reaches”

Sample 40529yu03 is from the upper Jinsha tributary and sample CJ1 is from the Yalong tributary to the mainstream. Populations of 200-260 Ma (~31%) and 360-470 Ma (~10%) in the sample CJ2 overlap with 230-270 Ma and 340-470 Ma populations in sample 40529yu03 from Shigu (Fig 3.3a & c), suggest that roughly 31-41% of the muscovite grains in the Yibin sample were derived from the upper Jinsha River (at Shigu). Because the 660-860 Ma muscovite population (~31%) in the mainstream sample from Yibin is only observed in the Yalong River (CJ1), we infer that most of muscovite grains dated in the range 660-860 Ma in the Yibin sample were derived from the Yalong River. The bedrock along the Jinsha River between Shigu and Yibin could also be a potential source of muscovite grains dated in the range 660-860 Ma. Small peaks around 5 Ma, 190 Ma, 300 Ma, 400 Ma and 470-520 Ma in the Yibin sample accounting for ~20%, were not observed in these two rivers. Therefore, we infer that these muscovite grains might come from the mainstream or other unsampled small tributaries.

However, the geochemistry of the muscovite grains shows a different picture (Fig 3.2a & b). Whereas the muscovite ages indicates that the Yibin sample is composed of sediments mainly from the upper Jinsha and partly from the Yalong River with minor contributions from other sources, the geochemistry indicates hardly any overlap. Only 4 of 20 (20%) muscovite grains from the Yibin sample fall within the upper Jinsha River field (Shigu) and only 3 of 20 (15%) muscovite grains from the Yibin sample overlap with the Yalong River field. The majority of the muscovite grains of the Yibin sample does not overlap with the Yalong and upper Jinsha rivers, suggesting that many muscovite grains may be not derived from these two rivers but from mainstream between Shigu and Yibin. The mismatch in provenance based on different methods may be explained by difference
in analyzed number between \(^{40}\text{Ar}/^{39}\text{Ar}\) dating (n>40 per sample) and chemical composition (n=20 per sample) and potentially incomplete sampling of the population in the latter case.

5.1.2 “Eastern part of Upper Reaches”

We use the plots of \(^{40}\text{Ar}/^{39}\text{Ar}\) muscovite ages to examine the ways in which muscovite age signals from the Jinsha, Min and Jialing rivers are expressed in the sample from the mainstream at Yichang (Fig 3.3). Although ~15% dated muscovite grains with ages of 330-460 Ma at Yichang were potentially derived from the Jinsha River, the age distributions of Yichang and the Jinsha River clearly show that the Jinsha River cannot be a major sediment supplier (Fig 3.3c & f). This result is in agreement with constraints of Pb isotope compositions of detrital K-feldspar (Zhang et al., 2014) and U-Pb ages of zircon (He et al., 2014). We note that the 200-260 Ma range (~13%) seen in the Yichang sample compares closely with ages observed in the Jialing and Jinsha rivers. This suggests that these muscovite grains were likely derived from these two rivers. The Yichang sample is dominated by grains dated as younger than 180 Ma (~72%): these ages correspond to those observed in the Min River (Fig.3d & f). We conclude therefore that the Min River is a major contributor (~72%) to sediment flux reaching Yichang. These data are corroborated by the major element geochemistry of the muscovite grains showing that ~65% (13 of 20) muscovite grains of the Yichang sample (CJ7) overlap with those of the Min River (Fig 3.2c & d). Although 5-7 data points (25-35%) of Yichang sample overlap with the Min and Jialing rivers fields (Fig 3.2c & d), the muscovite age distributions clearly show that the muscovite grains in the Yichang sample younger than 180 Ma (~72%) come from the Min River.

5.1.3 “Middle to Lower Reaches”

We compare the detrital muscovite ages in the modern Yangtze delta (Xing-1) with those from the major tributaries in order to constrain the provenance of the sediment flux now reaching the Yangtze delta. The age distribution of muscovite grains in the delta is very similar to that of the Yichang sample (CJ7) and different from those of the tributaries in the middle and lower reaches, implying that most of the muscovite grains were derived from the upper Yangtze River basin (Fig 3.3f & k). It is noteworthy that ~52% of the grains are younger than 90 Ma, which are uniquely found in the Min River and so confirming that it is the dominant source of muscovite grains currently reaching the Yangtze delta (Fig 3.3d & k). The Yangtze delta sample also yields 150-165 Ma (~10%) and 98-133 Ma (~18%) muscovite grains, which are seen clearly in the Xiang and Gan rivers and Yichang samples. The age range 205-225 Ma (~10%) in the Yangtze delta is observed in the Jialing, Gan, Zi and Xiang rivers, suggesting that these muscovite grains were derived from these rivers (Fig 3.3). Because the Yangtze delta yields age populations at 150-165 Ma (~10%), 98-133 Ma (~18%) and 205-225 Ma (~10%), corresponding to ages from the Xiang and Gan rivers and Yichang samples, it is not feasible to determine from \(^{40}\text{Ar}/^{39}\text{Ar}\) muscovite dating alone how many of these grains came from the upstream of Yichang (Fig 3.3). Hoang et al., (2010) only give the \(^{40}\text{Ar}/^{39}\text{Ar}\) ages of muscovite grains from a sand sample at the Yangtze delta and do not analyze the major elements of these muscovite grains. Therefore, we cannot
compare the geochemical composition of muscovite grains from the major river tributaries to those of the Yangtze delta to constrain the provenance of muscovites in the Yangtze delta.

5.1.4 Other factors influencing detrital muscovite age patterns

Potential drawbacks of our approach are 1) the effect of grain abrasion during sediment transport; 2) concentration differences in muscovite content in different tributaries masking the contributions of rivers with low muscovite contents and 3) incomplete analyses of the sample population (see 5.1); 4) widespread co-seismic landslides and enhanced erosion triggered by the 2008 M\text{w}7.9 Wenchuan earthquake; 5) the effect of the construction of dams in the Yangtze River basin.

We only dated the fraction of 200-500 mm and therefore lack the population of muscovite grains smaller than 200 µm. One might argue that most of the muscovite grains from the Jinsha, Jialing and Han rivers are not observed in the Yangtze delta because they were abraded into grains smaller than 200µm. But if so it is difficult to explain why the muscovite from the Min River is not affected by this process because the sampling locations of sample CJ2 (Jinsha River) and CJ3 (Min River) are very close, and hence dilution effects during transport in the mainstream of the Yangtze are expected to be comparable. In fact, the muscovite grains transported from the Min River to the delta have travelled further than those from the Han, Xiang, Zi and Gan rivers (Fig 3.1). Therefore, the observation that at least 52% of total muscovite grains in delta were derived from the Min River is unlikely to be caused by the preferential abrasion of muscovite in the Yangtze River.

To assess if high concentrations of muscovite in the Min River sediment causes the dominance of the Min River muscovite in the Yangtze delta, we counted muscovite grains in one gram of sieved sediment (200-500µm and 500-1000µm) for all major tributaries (Fig 3.4B). The concentration of 200-500µm muscovite of modern sediment in the Min River (177/g) is much lower than that of the Jinsha (594/g), Han (533/g) and Jialing rivers (209/g) and higher than the Xiang (52/g) and Gan River (165/g). The concentration of 500-1000µm muscovite in the Min River (490/g) is also not the highest and less than Han River (647/g). Therefore, we can rule out large concentration variations in muscovite in the sediment as being a major control on the dominance of the Min River muscovites in the delta sediments.

The Wenchuan 2008 earthquake is the strongest earthquake in the last 50 years in the Yangtze River basin and triggered widespread co-seismic landslides and significant erosion. The sediment load record from the gauging station in the lower reaches of the Min river allow us to examine whether the Wenchuan earthquake significantly increased sediment load in the Min River basin. The sediment load records during the period 2008-2012 after the Wenchuan earthquake do not increase significantly (http://www.cjw.gov.cn/zwzc/bmgb/). Large amount of materials caused by the co-seismic landsliding after the Wenchuan earthquake could be trapped by many large dams in the Min River basin, which means that our samples collected in 2012 in the Yangtze basin are not affected significantly by the Wenchuan earthquake.
Figure 3.4 A Grain size distribution of suspended sediment at Datong, Wuhan and Yichang in 1960-1980. Grain size data from the Wei et al. (1986). B: muscovite concentrations of samples from various tributaries. Number of muscovite grains counted in 1 gram sediment of respectively 200-500 and 500-1000 micron.

The record of sediment load (suspended load) before and after dam constructions can indicate to some degree the influence of dams on sediment transport. According to the record of gauge stations, the mean sediment load of the Jinsha River decreased from $2.3 \times 10^8$ t/yr in 1956-1969 to $1.5 \times 10^8$ t/yr in 2003-2010. The Min River decreased from $0.6 \times 10^8$ t/yr between 1954 and 1968 to $0.3 \times 10^8$ t/yr between 2003 and 2010 (Fig 3.5A). The average sediment load of the Min River is still much less than that of the Jinsha River after dam constructions. Although a large amount of sediment was stored by the Three Gorges Dam after the initial closure of the dam in 2003 (Fig 3.5A), it is located in the mainstream of the Yangtze between the Sichuan Basin and the Yangtze delta and would have affected the flux of sediment from the Min, Jialing rivers just as much as from the Jinsha River. Therefore, we suggest the dam construction is not likely to be the primary control on the dominated sediment supply from the Min River to the Yangtze delta.

In Fig 3.5B we summarize the muscovite contribution of each tributary (section 5.1.1-5.1.3) to the Yangtze delta based on the above age population and chemical compositions. It appears that the Min River basin may experience more rapid erosion than other tributaries. The Min River drains the Longmen Shan and Xianshui He Fault areas that are tectonically active (Fig 3.6) (Zhang et al., 2004). Moreover, these regions experience heavy summer monsoon rains and might be expected to facilitate more landslides and intense erosion (Fig 3.6). In contrast, much of the Jinsha River watershed above Shigu and most of the Yalong River lies in the central and eastern Tibetan Plateau where there is little precipitation and no rapid erosion (0.013-0.04 mm/yr) (Henck et al., 2011). Although our data are based on sediments deposited during and after the summer monsoon of 2012, already general longer term erosion patterns reveal differences between the different drainage basins. Previous $^{10}$Be analyses of river sands show 0.013-0.04 mm/yr erosion in the Jinsha River watershed above Shigu (Henck et al., 2011), while (Ouimet et al., 2009) report erosion rates to the east of the Jinsha River between 0.3 and 0.5mm/yr in the Yalong and Min rivers drainages. Moreover, Liu-Zeng et al. (2011) and Godard et al.(2010) report...
millennial erosion rates based on detrital $^{10}$Be data in the Min River basin of 0.5-0.8 mm/yr and 0.5-1 mm/yr, respectively. Therefore, erosion rates increase from west to east more than twenty-fold from 0.013-0.04 mm/yr in the Jinsha River to 0.5-1 mm/yr in the Min River basin. Moreover, $^{10}$Be measured in the middle and lower reaches (Yuan-Xiang rivers) gave rates of 0.03-0.05 mm/yr, which is much lower than those of the Min River basin (Chappell et al., 2006). Denudation rates inferred from thermochronometry data also parallel this trend in long-term exhumation rates. To the west, in the Jinsha River basin, the exhumation rate inferred from apatite and zircon U-Th/He thermochronometry is reported to be 0.38 mm/yr beginning at or before ca. 10 Ma (Ouimet et al., 2010). To the east of the Jinsha River, in the Yalong, Dadu rivers and Longmen Shan regions, exhumation rates are reported to be 0.5-2 mm/yr since 8-13 Ma, as indicated by numerous studies using a variety of thermochronological techniques (Godard et al., 2009; Kirby, 2008; Kirby et al., 2002).

5.2 Comparison with sediment load

We collected sediment load data recorded by gauging stations over the period 1956-1969 and 2003-2010 in the Yangtze River basin (Fig 3.5A & B). The data sources we used include observational data from the Yangtze River Water Conservancy Committee, Ministry of Water Resources of China (http://www.cjw.gov.cn/zwzc/bmgb/) and data extracted and digitized from Gao et al. (2015). The impoundment of the Three Gorges Dam in 2003 created the largest hydroelectric dam in the world. The average downstream sediment load in the period of 2003-2010 was substantially affected by the construction of the dam. Average sediment load in the period of 1956-1969 was not greatly affected by dams as almost all large dams in the Yangtze River basin constructed after 1970. The sediment contribution of the various tributaries to Datong has been adjusted by taking into account the deposited sediment in lakes and dams. Calculations of sediment contribution of the various tributaries to Datong are further described in Gao et al. (2015). The sediment load record at Datong station is representative for the discharge from the Yangtze River to the sea.

The contribution of each tributary to the delta was calculated from the overlap in age distribution and geochemistry of muscovites between main stream and tributaries (Fig 3.5B). If one age population in the delta overlaps with more than one tributary, we cannot calculate the contribution of a tributary to this age population in the delta. Therefore, the percent of this age population in the delta is shown as uncertain contribution of this tributary in Fig 3.5B. The sediment contribution of different tributaries calculated from sediment load is compared to those estimated from ages and chemical compositions of muscovite grains summarized in Fig 3.5B. The sediment load of the Min River only accounts 8.8% of that at Datong in the period of 1956-1969 (Fig 3.5B). However, the sample collected at the Yangtze delta is rich in muscovite from the Min River (>52%) and poor in muscovite from the Jinsha (<10%) and Jialing River (<10%). In contrast, the sediment load of the Jinsha River at Pinshan accounts for 35% of that at Datong in the period of 1956-1969 and 24.1% in the period of 2003-2010 (Fig 3.5B). According to the age distributions, the Han River only provided ~2% of muscovite grains to the delta, but its sediment load accounts for 19% at the Datong station in the period of 1956-1969. The contribution of the Jialing River to the sediment load at Datong is 24.3% in the period
of 1956-1969, but muscovite age data suggest that less than 10% of sediment at Datong originates from the Jialing River. The proportion of sediment contributed by various tributaries to delta calculated from sediment load does not yield a good match to those based on the ages and geochemistry of muscovite grains. Muscovite data suggest that the Min River basin experienced much more intense erosion than other tributaries, but sediment load data imply a general erosion pattern of higher erosion rates in the Jinsha and Jialing rivers before the dam construction.

**Figure 3.5** Histograms showing the average sediment load of various tributaries (A), and B) the proportion of sediment contributing to the delta from major tributaries based on sediment load and muscovite ages and compositions.

The erosion patterns based on muscovite and sediment load might be very different in part because of the drawbacks mentioned above (section 5.1.4). However, this mismatch in erosion patterns is unlikely to be completely controlled by these mechanisms. The average sediment load data of 14 years (1956-1969) were used to calculate the contribution of different tributaries and bias caused by fluctuation in sediment load in the Yangtze River was therefore significantly reduced. The catastrophic flooding events in 1954 and 1998 in Yangtze river was not in periods of 1956-1969 and 2003-2010. Moreover, we use the average sediment data of these periods, the bias caused by landslides or rare (less than once every 10 years) severe weather conditions related to climate change in source area is also excluded. Therefore, this mismatch in erosion patterns is unlikely to be dominated by such sporadic effects. We contend that this mismatch can be attributed mainly to different erosion patterns recorded by these two methods. The suspended sediment load is sensitive to the influence of recent human activities and climate change in the Yangtze River basin (Yang et al., 2005; Zhang et al., 2006) and, in principle, gives contemporary erosion patterns. This is consistent with the observation that sediment discharge record of ten gauging stations on mainstream of the Yangtze River from May to October covers >70% of the total sediment load (Yangtze Sediment Bulletin, 2008-2012). The mismatch between muscovite and sediment load data could be explained by changes of the erosion patterns in the Yangtze River in the past. The erosion patterns based on muscovite data are similar to the cosmogenic nuclide data implying that the millennial scale erosion rates in the Min River basin are much higher than those of other tributaries (Chappell et al., 2006; Godard...
et al., 2010; Henck et al., 2011; Liu-Zeng et al., 2011; Ouimet, 2010). This suggests that the muscovite data from the modern sediment might represent an “old” erosion pattern, but the sediment load data instead would indicate a “young” erosion pattern in direct response to human activity in the catchment area. The “old” erosion pattern suggests that the upper Yangtze River experienced more intense erosion than middle-lower reaches and the Min River experienced the most intense erosion in the upper Yangtze. The “young” erosion pattern shows that the Jinsha and Jialing rivers are experiencing more intense erosion than other tributaries. The “old” erosion pattern recorded the natural sediment budget controlled by natural system and “young” erosion pattern is controlled by human impact.

Why do muscovite grains in the modern sediment from the delta record “old” erosion pattern? We suggest that varying sediment transport rates could be a possible explanation. These muscovite grains were not transported from the source areas recently. Hoang et al. (2010) suggest that zircon in the Red River system need ~8ka to travel from the source to the delta, similar to the 5-10 ka years transport time inferred from Indus and Yangtze rivers zircons (Alizai et al., 2011; He et al., 2014). We suggest that the medium grained muscovite grains in the Yangtze drainage would require a long time to travel from the source to the delta for the following reasons: 1) The grain size data of suspended sediment at the Datong, Wuhan and Yichang (Fig 3.4A) show that the amount of grains >250 μm in suspended sediment is very low in the middle and lower reaches of the Yangtze River. Moreover, the grain size of muscovite in suspended sediment in the Yangtze River is <0.1mm (Wei et al., 1989). This suggests that the 200-500 μm muscovite grains in the Yangtze River are likely to be transported as bed load in the middle and lower reaches. The sediment grain size data in transit at various depths of the Ganges and Brahmaputra rivers also suggest that 200-500 μm muscovites were transported as bed load or not far above bed load (Garzanti et al., 2011). 2) Although the density of muscovite (2.82 g/cm³) is lower than that of zircon (4.65g/cm³), the medium sized muscovite (200-500 μm) in this study is larger than dated detrital zircons (60-125 μm) from the Yangtze River (He et al., 2014). There is no evidence to support that 60-125 μm zircon transports slower than 200-500 μm muscovite in large rivers. 3) The Yangtze River (6300km) is much longer than the Red River (1280km) and Indus River (3180km) and transport will therefore take longer. 4) Complex river channel systems and big lakes in the middle and lower reaches (1893km) of the Yangtze River can trap sediment before it moves downstream into sea. In recent studies, long-term sediment storage on the order of 1000 years in the Yangtze River has been shown (Stanley and Chen, 2000).

5.3 A mechanism to understand the contrasting sediment transport signals.

The mismatch between “old” and “young” erosion patterns implies that the erosion pattern changed in the recent past. The tectonic setting and hill slope angles in the region change slowly at millennial timescales. As we see a more abrupt change, we suggest, therefore, that tectonics and slope are unlikely to have greatly affected the regional erosion patterns along the Yangtze streambed on timescales less than 10ka.

We argue that the contrasting sediment transport signals could be either the response to Holocene climate variation, or to the progressive impact of human settlement in the catchment area. First we discuss the scenario of climate forced variation of sedimentation
patterns. Rapid increase of sediment accumulation rate at the Yangtze delta started after ~1900 yr B.P and in the upper stream started after ~1000 yr B.P (Fig 3.7A, C & F), while the intensity of the Asian monsoon shows gradual weakening from ca 7000 yr B.P and an intensification after ~ 500 yr B.P. This general trend is punctuated by eight weak Asian monsoon Bond events centered at 0.5, 1.6, 2.9, 4.4, 5.4, 6.2, 7.4 and 8.3 ky B.P (Fig 3.7A). Fig 3.7 shows that the changes of pollen (Poaceae and Quercus) are not consistent with that of the climate. These changes in sediment accumulation rate and pollen content at ~1900 yr B.P and ~1000 yr B.P are not consistent with these events in Holocene (Fig 3.7A, C and F). Moreover, reconstructed past precipitation based on Δδ^{18}O data from a stalagmite at Heshang Cave (location is shown in Fig 3.1) suggests many relatively stronger precipitation events (the strongest precipitation was at ~6200 yr B.P) (Fig 3.7A), but these two significant increases in sediment accumulation rate started at ~1900 yr B.P and ~1000 yr B.P (Fig 3.7A, C & F). In addition, Fig 3.6 shows that the current heavy mean annual precipitation in the Min, Xiang and Gan river basins is not consistent with the slow erosion based on the modern sediment load data in these areas. The mean annual precipitation distribution is lower in the Jinsha and Jialing river basins. This is not in agreement with intense modern erosion based on the modern sediment load data in these areas. The arguments summarized here would suggest that there is no direct relationship between the climate and erosion in the last ~1900 yr B.P.

Instead we suggest that the changes in erosion patterns are related to increasing impact of human settlement of the catchment area. It has been recognized that human activities (farming and deforestation and mining) can accelerate erosion (He et al., 2014; Reusser et al., 2015; Wan et al., 2015). A new settlement is often followed by a pulse of sediment delivery into rivers. Fig 3.6 shows that earliest human settlements appeared in the middle and lower reaches before 6ka and extended to the upper Yangtze River during 6-3ka and significantly increased since 3ka in the Jinsha River basin (Fig 3.6). This is consistent with the intense contemporary erosion in the Jinsha River basin. This implies that human activities would have started to influence the erosion later than 6ka in the upper Yangtze and only substantially enhanced erosion rates later than 3ka.

The sediment accumulation rate in the Yangtze delta has increased abruptly since ~1900 yr B.P, which corresponds well to the changes of pollen and heavy metal concentration in sediment cores. The pollen records from core sediment in the Poyang Lake in the middle reaches show a remarkable increase of herbaceous pollen (Poaceae) and decline of arboreal pollen (Quercus) at ~1900 yr B.P (Fig 3.7E). These changes can be related to an expansion of regional deforestation and concomitantly increased agriculture activities due to a rapid increase in population in Han Dynasty times (2206-1780 yr B.P) (Hsü, 1978). The population increased from ~13 million at the time of the early Han dynasty to ~70 million at the time of the middle Han Dynasty (Lu and Teng, 2000)(Fig 3.7G). Although the Yangtze River catchment covers ~20% of China, the population of the Yangtze River catchment increased with the increase of population of the whole country (Lu and Teng, 2000). There was a rapid increase in the concentrations of Cu, Ni and Cd in the sediments around ~1900 yr B.P in the Liangzi Lake and the delta (Lee et al., 2008; Liu et al., 2010)(Fig 3.7D & F). The expansion of agricultural activities due to a rapid increase in population may have caused an increase in the utilization of metal smelting for
manufacturing of tools from the start of the Iron Age. Moreover, burning trees to produce carbon for metal smelting may have been a factor that increased deforestation and hence facilitated erosion. Deforestation and mining decreased the vegetation which caused the exposure of erodible soil to rainfall (Gyssels et al., 2005). Soil will be quickly washed away by heavy rain when the anchor of tree roots is lost (Gyssels et al., 2005). The removal of the vegetation also increased the average velocity of water flow along the surface of the terrain and decreased its overall residence time and in turn increased the runoff volumes, which added to acceleration of the erosion intensity (Dunne et al., 1991). We rule out that the changes in precipitation cause intensification of soil erosion around ~1900 yr B.P because no significant changes in precipitation were observed at that time.

The magnetic sedimentary record in the Erhai Lake (Fig 3.1) points to an abrupt increase in erosion after 1000 yr B.P, which is consistent with an increase in pollen concentration of Poaceae in Erhai Lake (Fig 3.7B) in the upper reaches. The sediment accumulation rate in the Shayema Lake showed a remarkable increase since ~1000 yr B.P, which corresponds with an increase in pollen concentration of Gramineae in this lake (Fig 3.7C). This change can be related to the quick increase of the population to more than 100 million people after ~1000 yr B.P in China (Fig 3.7G). Moreover, a large-scale migration event into upper reaches of the Yangtze River from north of China occurred during Tang Dynasty (~1382-1003 yr B.P) (Tang, 2014). We suggest that the effects of human settlement gradually overwhelmed natural erosion since ~1000 yr B.P in the upper reaches. In summary, increased population during the Iron Age was accompanied by rapid development of agriculture in the upper reaches of the Yangtze River, and can be identified as the cause of intensification of soil erosion. All the foregoing suggests that the human
Figure 3.7 Comparison of different records in the Yangtze River basin since 9000 cal yr B.P. Vertical gray band indicates the time period dominated by human activities. Sample locations are shown in Fig 3.1. A: The summer monsoon proxy of stalagmite δ¹⁸O at Dongge Cave (Wang et al., 2005) and reconstructed past rainfall based on Δδ¹⁸O data from stalagmite at Heshang Cave (Hu et al., 2008). Vertical yellow bars denote the timing of the Bond events. B: Erhai lake sediment magnetic susceptibility curve used as an erosion proxy $[\chi_{lf}]$, together with pollen record (Dearing et al., 2008). C: Pollen record of core sediment in Shayema Lake in the upper reaches (Jarvis, 1993). D: Cu and Ni concentration of sediment in Liangzi Lake in the middle Yangtze River reaches (Lee et al., 2008). E: Pollen record of core 103B in Poyang Lake in the middle reaches (Jiang and Piperno, 1999). F: Accumulation rate based on age and depth data of core CM97 (Hori et al., 2001) and downcore variations in the ratios of Cu and Cd to Al of core ECS0702 in the Yangtze delta (Liu et al., 2010). G: The population change in China (Lu and Teng, 2000). PRC-People’s Republic of China.
impact on erosion and consequently sediment load gradually supersedes long-time natural factor control of erosion in the Yangtze River basin, especially since ~1900 yr B.P in the middle-lower reaches and ~1000 yr B.P in the upper reaches.

Based on detrital U-Pb zircon data from the Yangtze River, He et al. (2014) suggest that the Han, Xiang and Jialing rivers are the dominant sediment contributors to main stream in the past and this erosion pattern is mainly controlled by the disturbance of landscape by human settlement in combination with the specific stream power in the middle Yangtze River after ~5000 BC. In contrast to He et al. (2014), our muscovite data imply that the Min River is the most important sediment contributor to delta. The difference of these studies can be explained as follows: 1) Although both zircon and muscovite are assumed to be transported as bed-load, due to the different density and grain size of zircon (4.65g/cm$^3$, 0.63-125 µm) and muscovite(2.82g/cm$^3$, 250-500 µm), the transport time of zircon and muscovite from the source to the delta can be different. Therefore, they record different erosion pattern of the Yangtze River at different time. 2) The closure temperatures of muscovite (350 - 450°C) (Haines et al., 2004) and zircon (>900 °C, Lee et al. (1997)) are different. Muscovite reveals more about the immediate tectonic information of source area compared to zircon (Haines et al., 2004). Although this implies that the age distributions on zircon and muscovite will be different, the population overlap between stream and delta samples should be the same, if the would reflect the same erosion processes at the same time.

6 Conclusions

We present $^{40}$Ar/$^{39}$Ar ages and geochemical analyses of detrital muscovite grains from the Yangtze River catchment. The muscovite-based sediment budget is compared to standard sediment load data from gauging stations along the river. The results demonstrate that the following:

1. Comparison of muscovite ages from the Yangtze delta with those of different tributaries shows that the Min River is a major supplier of sediments to the delta, suggesting that the Min River region must have experienced rapid erosion.

2. The $^{40}$Ar/$^{39}$Ar age distributions of detrital muscovite grains from the delta record the original erosion pattern that the Min River, in the eastern edge of the Tibetan Plateau, indicating that it was experiencing more intense erosion than other regions. This pattern was not significantly affected by human activities before late Holocene.

3. The mismatch between different erosion patterns based on sediment load data and the information on sediment transport derived from muscovite ages suggests that erosion pattern in the Yangtze River basin was altered significantly after ~1900 yr B.P. We contend that the advent of an Iron Age agricultural society in the catchment area during this period is the most likely cause for this change in sediment transport.

4. The differences in erosion patterns of detrital muscovite and zircon records found for the Yangtze River at different times appear to be caused by their differences in physical and geochemical properties.
Chapter 4

Detrital geochronology and geochemistry of the Jianghan Basin: implications for the Cenozoic evolution of the Yangtze River

Xilin Sun, Chang’an Li, K.F. Kuiper, Jietao Wang, Pieter Vermeesch, Zengjie Zhang, Juxing Zhao, J.R. Wijbrans


The geometry and evolution of rivers originating from the Tibetan plateau are influenced by topography and climate change during the India-Asian collision. The Yangtze River is the longest among these rivers and was assembled by amalgamation of many rivers in the eastern Tibetan Plateau. The timing of these capture events is still controversial. Here we use geochemistry, $^{40}$Ar/$^{39}$Ar dating of detrital muscovites and detrital zircon U-Pb ages to constrain the provenance of late Cenozoic sediments in the Jianghan Basin in the middle reaches of the Yangtze river. The combined data suggest that the upper Yangtze reaches is embodied by the Qingyi, East Min, Jialing and Jinsha rivers upstream of the Three Gorges and is the sediment source to the Jianghan Basin before late Pliocene (~3.5 Ma). This implies that the Three Gorges must have formed before the Quaternary (>3.5 Ma) in agreement with recent studies. One river, perhaps the paleo-Han River, originating from the Dabieshan flowed into the center of the Jianghan Basin during the late Pliocene ~3.5-2.6 Ma. Sediment from the upper Dadu River appeared in the Jianghan Basin somewhere between 2.1 and 1.2 Ma and this suggests that the originally south flowing upper Dadu River was captured by rivers of the Sichuan Basin around that time. This capture event is closely linked to strike-slip tectonism and surface uplift in the eastern Tibetan Plateau.
1 Introduction

The India-Asia collision caused the uplift of the Tibetan Plateau and triggered large scale climate change. This collision also changed the continental topographic gradient, which directly influences the major drainage patterns of rivers in the periphery of the Tibetan Plateau. The Yangtze River today originates from the Tibetan Plateau and is one of the largest rivers in the world. The Yangtze transports large quantities of terrestrial material from the Tibetan Plateau into the East China Sea. Several lines of evidence (Clark et al., 2004; Clift et al., 2006a; Clift et al., 2008) support the hypothesis that the Dadu, Yalong and upper Jinsha rivers in the eastern Tibetan Plateau flowed southward into the Red River (Fig 4.1) before the Miocene. Due to the uplift of the Tibetan Plateau, these rivers changed course and became connected to the middle-lower reaches of the Yangtze River. Although the exact timing of the connection and thus the “birth” of the Yangtze River has been studied already for almost one century (Clark et al., 2004; Clift et al., 2008; Li, 1924; Willis et al., 1906), it remains a controversial topic. Several previous studies suggest that formation of the Yangtze River can be dated back to the Eocene-Miocene (Clift et al., 2006a; Clift et al., 2008; Hoang et al., 2009; Richardson et al., 2010; Zheng et al., 2013), Pliocene (Fan et al., 2005; Shao et al., 2012) or, alternatively, to the middle-late Pleistocene (Li et al., 2001; Zhang et al., 2008). Moreover, there are only a few constraints on the timing and events of reorganization of rivers in what is now called the “upper” Yangtze drainage system that were ultimately captured by the lower Yangtze River to form the present river.

Single proxies of chemical, mineralogical or isotopic data provide only limited information about the sediment provenance and evolution of the Yangtze River. Multiple chemical and isotopic indicators of single mineral grains can extract more robust information about sedimentary provenance. Here we combine the geochemistry and Ar/Ar ages of detrital muscovites with detrital zircon U-Pb geochronology to constrain the sediment provenance of the late Cenozoic sediments in the Jianghan Basin in the middle reaches of the Yangtze River. This location lies just east of the Three Gorges region representing the connection between the upper and middle reaches. Detrital zircon and muscovite ages are a sensitive tool to constrain the sediment provenance (Najman et al., 1997; Hoang et al., 2010; Zheng et al., 2013). Zircon U-Pb ages record long-term magmatic and high grade metamorphic history because of its physical robustness and high closure temperature (>900 °C) (Lee et al., 1997). Muscovite is less resistant to physical abrasion and reveals more information about the more recent tectonic history of the source area due to its lower closure temperature (350-425 °C) (Harrison et al., 2009). Muscovite is less likely to survive multiple orogenic erosion-depositional cycles compared to zircon. In this study, the combination of detrital muscovite and zircon data as applied to modern river sediments and material obtained from the Jianghan Basin reveals new information about the “birth” of the Yangtze river by providing new age constraints on the formation of the connection between the upper and middle reaches represented by the formation of the Three Gorges cutting through the orographic barrier and on the changes in flow direction from South to East for the Dadu river.
2 The Yangtze River system

The modern Yangtze River is the longest river in Asia with a length of 6300km. It originates in the Tibetan Plateau and flows through deep mountain valleys from the eastern Tibetan Plateau towards the Sichuan Basin (Fig 4.1a). From the eastern Sichuan Basin, the Yangtze River incises the Three Gorges valley into the Jianghan Basin and finally flows into the East China Sea. The Yangtze River is generally divided into three segments: the upper reaches, defined from the headwaters to the city of Yichang immediately downstream of the Three Gorges; the middle reaches, defined from Yichang to Hukou; and the lower Yangtze defined from Hukou to the estuary (Fig 4.1a).

The Yangtze River is primarily situated in the Yangtze Craton, surrounded by the Qiangtang Block, the Songpan-Garze Block, Qinling-Dabie orogenic belt and Cathaysia Block (Fig 4.1b). The major tributaries are characterized by different tectonic settings and lithologies: most of the Jinsha, Yalong and Min rivers (1, 2 & 3 in Fig 4.1b) drain the Songpan-Garze Block which is covered by deformed and locally metamorphosed Middle to Late Triassic turbidites and intruded by many Triassic and Cenozoic magmatic rocks (Roger et al., 2010). Enkelmann et al. (2007) and Weislogel et al. (2006, 2010) suggest that the southeastern and eastern Songpan-Garze complex was derived from the Qinling-Dabie orogen in the Middle to Late Triassic. The two most important fault systems on the eastern Tibetan Plateau (Xianshuihe and Longmenshan Faults) are located in the Dadu and East Min river catchment areas. The drainage basin of the Jialing River (4 in Fig 4.1b) is characterized by metamorphic rock, Jurassic red sandstone and Quaternary loess deposits. The Han River basin (5 in Fig 4.1b) is characterized by metamorphic rocks, carbonate, the Mesozoic intrusive igneous rocks and clastic sediments (Dong et al., 2011). Mesoproterozoic-Neoproterozoic orogenies have a strong impact on this belt. The Zi and Xiang rivers (6 and 7 in Fig 4.1b) contain outcrops of old medium-low grade metamorphic rocks, carbonate rocks, and Quaternary clastic sediments. Based on the discrepancies of physical and chemical properties of muscovite and zircon, the muscovite is expected to provide clearer distinction between rivers on the Eastern Tibetan Plateau (Dadu and East Min rivers) and other tributaries because its lower closure temperature records the recent tectonism in the Dadu and East Min rivers. Zircon is expected to record older geological events because its physical robustness and high closure temperature.

The Jianghan Basin is located immediately downstream of the Three Gorges in the middle reaches. This basin developed along the southern margin of the Tongbai-Dabieshan Orogen and occupies an area of ~28000km². It is a typical synorogenic foreland basin associated with the Dabies Orogen but has been influenced by subsequent extensional faulting and rifting (Liu et al., 2005). The Yangtze River flows across the Jianghan Basin from west to east and has deposited a large amount of sediment. The sedimentary record deposited since the late Cenozoic in the Jianghan Basin could therefore, in principle, be used to reconstruct the development of the Yangtze River.

Two drilled cores were taken from two nearby towns, Zhoulao (ZL) and Xingou (XG) which are located 10km apart in the depocenter of the Jianghan Basin (Fig 4.1d). No significant unconformity was observed in these two cores, suggesting a rather complete record without major hiatuses since the late Cenozoic in the Jianghan Basin.
(Fig 4.2). Minor hiatuses will be present inherent to the fluvial sedimentary system. Core ZL was drilled to a depth of 300.47m, with an average recovery of 85%. Depositional age constraints are provided by the recognition of two geomagnetic polarity reversals at depths of resp. 82m (Brunhes/Matuyama of 0.78Ma) and 260m (Matuyama/Gauss of 2.58 Ma) (Zhang et al., 2008). Linear extrapolation of the sedimentation rate implies an age of ~2.8Ma for the base of core ZL. Core XG was drilled to a depth of 400.59m with 96% average recovery (Fig 4.2). Geomagnetic reversals are recognized at 81m (Brunhes/Matuyama of 0.78Ma), at 250m (Matuyama/Gauss of 2.58 Ma) and at 365m (Gauss/Gilbert of 3.57 Ma)(Zhang et al., 2008). Linear extrapolation of the sedimentation rate yields an age of ~3.93Ma for the base of core XG.

Figure 4.1 Map showing the research areas in the Yangtze River basin. Sample sites of previous work (Sun et al., 2016) are shown for comparison. The white and black circles are sample locations for respectively muscovite samples from Sun et al. (2016) and zircon samples from He et al.(2014) and Yang et al.(2012). The dark gray circles represent the sample locations of the Min River tributaries in this study. The stars indicate the position of cores Zhoulao (ZL) and Xingou (XG). The white arrows indicate flow direction. The red dashed-line (A-A’) in d shows the position of the cross section of Quaternary sediment in the Jianghan Basin. The shaded area in c represents the Gonggashan granite (GSG).

3 Sampling and analytical methods
3.1 Sample description

Six sand samples (ZL1-ZL6) were taken from the core ZL at ~79, ~126, ~160, ~220,
~280, and ~300 m, corresponding to depositional ages of ~0.7 Ma, ~1.2 Ma, ~1.8 Ma, ~2.1 Ma, ~2.6 Ma and ~2.8 Ma, respectively, based on magnetostratigraphic interpolation (Fig 4.2). One sample (XG) was collected from the Xingou core at a depth of 350 m corresponding to a depositional age of ~3.5 Ma (Fig 4.2). In addition, we collected four samples from three major tributaries of the Min River, i.e. Dadu, Qingyi and East Min rivers (Fig 4.1c) to further constrain the source of the remarkable young age population identified in the Min River (Sun et al., 2016). Approximately 2 kg medium grained sand was collected at each sample location. Sample information is given in Table 4.1.

Table 4.1. Summary of sample information (Ms = muscovite; Zrn = zircon)

<table>
<thead>
<tr>
<th>Type</th>
<th>Lab-ID</th>
<th>Longitude</th>
<th>latitude</th>
<th>Locations</th>
<th>Depth (m)</th>
<th>age (Ma)</th>
<th>Mineral</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core ZL</td>
<td>ZL1</td>
<td>112°59′10″ 30°01′57″</td>
<td>Zhoulao Town</td>
<td>79</td>
<td>0.7</td>
<td>Ms and Zrn</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ZL2</td>
<td>126</td>
<td>Zhoulao Town</td>
<td>160</td>
<td>1.2</td>
<td>Ms and Zrn</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ZL3</td>
<td>220</td>
<td>Zhoulao Town</td>
<td>281</td>
<td>2.1</td>
<td>Ms and Zrn</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ZL4</td>
<td>300</td>
<td>Zhoulao Town</td>
<td>300</td>
<td>2.8</td>
<td>Ms and Zrn</td>
<td></td>
</tr>
<tr>
<td>Core XG</td>
<td>XG</td>
<td>112°58′06″ 30°07′54″</td>
<td>Xingou Town</td>
<td>350</td>
<td>3.5</td>
<td>Ms</td>
<td></td>
</tr>
<tr>
<td>East Min</td>
<td>M-LS</td>
<td>103°24′58″ 29°37′17″</td>
<td>Leshan</td>
<td>-</td>
<td>-</td>
<td>Ms</td>
<td></td>
</tr>
<tr>
<td>Qingyi</td>
<td>QYR</td>
<td>103°41′17″ 29°35′30″</td>
<td>Leshan</td>
<td>-</td>
<td>-</td>
<td>Ms</td>
<td></td>
</tr>
<tr>
<td>Dadu</td>
<td>DDR-LS</td>
<td>103°33′11″ 29°24′58″</td>
<td>Leshan</td>
<td>-</td>
<td>-</td>
<td>Ms</td>
<td></td>
</tr>
<tr>
<td>Dadu</td>
<td>DDR-SM</td>
<td>101°20′55″ 29°13′38″</td>
<td>Shimian</td>
<td>-</td>
<td>-</td>
<td>Ms</td>
<td></td>
</tr>
</tbody>
</table>

3.2 Analytical methods

Detrital muscovite (200-500 µm) and zircon (63-125 µm) grains were separated from the samples using standard heavy liquid and magnetic methods followed by handpicking. Muscovites of ZL1-ZL2 and ZL4-ZL6 were dated with $^{40}$Ar/$^{39}$Ar and zircons of ZL1, ZL3-4 and ZL6 were dated with U-Pb. Sample ZL3 yielded insufficient muscovite grains for $^{40}$Ar/$^{39}$Ar dating. Zircon data of sample ZL2 were already published in Wang et al. (2009). The muscovite was randomly split into two aliquots for electron microscope analysis and $^{40}$Ar/$^{39}$Ar dating. The muscovite grains from the first aliquot were mounted on a double-side tape, cast in epoxy resin and polished to expose an internal surface for electron microprobe analysis. The chemical compositions of the muscovite grains were measured by JEOL JX-A8800M electron microprobe at VU University Amsterdam. Wavelength dispersive spectrometers were used with 20 nA beam current and 15 KV accelerating voltage. The Si, Fe, Mg and Al contents of muscovite in metamorphic rocks are variable according the Tschermark substitution ($\text{Mg}^{2+} + \text{Fe}^{2+})\text{Al}^{3+} + \text{Si}^{4+} = \text{Al}^{3+} + \text{Si}^{4+} + \text{Al}^{3+} + \text{Si}^{4+}$) (Massonne and Szpurka, 1997). We therefore use ratio of Al/(Fe+Mg+Si) to place constraints on sediment provenance in this study.

The muscovite grains from samples ZL1-ZL2 and ZL4-ZL6 were packaged in Al-foil and stacked in quartz tubes with flux monitor (Drachenfels sanidine (DRA; 25.52±0.08 Ma) (Wijbrans et al., 1995)). Note that this age is based on the 24.99 ± 0.07 Ma reported
in Wijbrans et al. (1995) relative to 27.92 Ma Taylor Creek Rhyolite sanidine (TCs) and using Steiger and Jäger (1977) decay constants. In combination with the intercalibration factor 1.0112 ± 0.0010 for Fish Canyon Tuff sanidine (FCs) and TCs from Renne et al. (1998) and the FCs of 28.198 ± 0.022 Ma of Kuiper et al. (2008) relative to Steiger and Jäger (1977) this converts to the aforementioned 25.52 ± 0.08 Ma. Samples ZL1-ZL2 and ZL4-ZL6 were irradiated in the P3 position of the HFR Nuclear Reactor for 18h in Petten, Netherlands. The muscovite grains from samples M-LS, QYR, DDH-LS, DDH-SM and XG were placed into Al-foil packages and sealed with flux monitor (DRA) into Al-containers with 18.8mm diameter and 3.3mm depth for irradiation. These six samples were irradiated for 18 hours in CLICIT Facility in Oregon State University Radiation Center. Muscovite 40Ar/39Ar age determination of samples ZL1-ZL2 and ZL4-ZL6 were conducted at the Argon Geochronology Laboratory of the Vrije Universiteit Amsterdam. Single muscovite grains were placed into 2mm-diameter holes of a 185-hole copper disk that was heated overnight at 150°C in an ultra-high vacuum sample house. A 25W Synrad CO2 Laser Instrument was used to fuse the single muscovite grains. A cold trap (-70 °C) was used in the extraction line to trap volatilities (e.g. H2O and H2S). Sample gas was then cleaned by exposure to SAES St707 (Fe-V-Zr alloy) getters. Data were collected using a Hiden HAL 3F Series 1000 Pulse Ion Counting Triple Filter quadrupole mass spectrometer (Schneider et al., 2009). Procedural blanks were measured between every four unknowns. The muscovite grains from samples M-LS, QYR, DDH-LS, DDH-SM and XG were analyzed with a ThermoFisher HELIX-MC in the same laboratory, equipped with identical laser instrumentation and purification line. The program ArArCALC2.5.2 was used for data reduction and age calculation (Koppers, 2002).

Detrital zircon grains from samples ZL1, ZL3, ZL4 and ZL6 were mounted in epoxy and polished to expose internal surfaces for age determination. Detrital zircon U-Pb ages were determined by laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS) at the State Key Laboratory of Geological Processes and Mineral Resources, China University Geosciences (Wuhan). A 193nm ArF excimer laser ablation system was used to ablate 24μm circular spots on zircon grains. In-run analysis of zircon standard 91500 was conducted after every five unknowns. Argon was used as the carrier gas to transport the ablated materials from the laser ablation house to the ICP-MS. Standard NIST610 was used to calculate the content of trace elements and analyzed twice every 20 analyses. Integration of background and off-line selection and time-drift correction and analytical signals, and quantitative calibration were performed using in-house software ICPMSDataCal (Liu et al., 2010). In this study, 206Pb/238U ages are used for zircons with 207Pb/206Pb ages <1000 Ma, and 207Pb/206Pb ages for the older ones following the convention of Compston et al. (1992).

The number of analyzed grains per sample depends on the complexity of the detrital age distribution with simple, unimodal distributions requiring only a few dozen grains while more complex, multimodal distributions require 100 or more grains (Vermeesch et al., 2016). Because the zircon age distributions in this study are considerably more complex than the muscovite age distributions in our cores, we analyzed 99-130 zircon grains and only 49-61 muscovite grains per sample (Fig 4.4). For the Min River sample, 30 grains were analyzed (Fig 4.4a-d), ensuring with 95% certainty that no fraction greater than 15% was missed from the underlying detrital population (Vermeesch, 2004).
Figure 4.2  a) Lithological logs for the Zhoulao and Xingou cores. The dashed lines represent the correlations of the cores to the GPTS (modified from Zhang et al. 2008). Sample positions of this study are indicated. b) Cross section of Quaternary sediment in the Jianghan Basin (modified from Quaternary geological survey report of the Jianghan Basin in the Hubei province). The position of the cross section is shown in Fig 4.1d (A-A').
In order to constrain the potential source area of the sediments from the two cores, we compare our new data with the published muscovite geochemistry (Appendix 4A), \(^{40}\text{Ar}/^{39}\text{Ar}\) and zircon U-Pb ages from the major tributaries in the Yangtze basin (Appendix 4A). The full dataset comprises of 18 samples, 868 muscovite \(^{40}\text{Ar}/^{39}\text{Ar}\) ages, 1994 zircon U-Pb ages and 279 EMP analyses. It is difficult if not impossible to make geological sense of such ‘Big Data’ (sensu Vermeesch and Garzanti, 2015) without statistical help. In a first layer of simplification, we compute a table of Kolmogorov-Smirnov dissimilarities for each of the three datasets (muscovite \(^{40}\text{Ar}/^{39}\text{Ar}\), zircon U-Pb, and Al/(Fe+Mg+Si) in muscovite). We then visually approximate these two-dimensional tables as two-dimensional configurations of points by Multidimensional Scaling (MDS; Vermeesch, 2013). These MDS configurations allow a graphical assessment of the salient similarities and differences between the samples for each of the three datasets. In a second layer of simplification, we combine the three dissimilarity measures in a single three-dimensional matrix. Feeding this data structure into a ‘three-way’ MDS algorithm fits the entire dataset with two pieces of graphical output: a ‘group configuration’ showing the (dis)similarities between the samples, and a scatter plot of ‘source weights’ for each of the provenance proxies (Vermeesch and Garzanti, 2015).

4 Results
4.1 Microprobe analysis

The geochemistry of muscovite grains from the ZL and XG cores (Fig 4.2) was compared with the geochemistry of muscovites from the major tributaries to assess the compositional variability in the detrital grains (Fig 4.3). The muscovite geochemistry for the Min, Jialing and Jinsha rivers and mainstream Yichang sample are obtained from previous work (Sun et al., 2016). We analyzed the geochemistry of muscovites from the Zi and Han and Xiang rivers in this study (same samples in Sun et al. (2016)). The Al/(Fe+Mg+Si) ratio of muscovites in samples XG and ZL6 are remarkably different from those of the upper four samples (Fig 4.3). Muscovite grains in samples ZL1-ZL2 and ZL4-ZL5 and the Jialing River are characterised by high Al/(Fe+Mg+Si) ratios. Consequently, these samples plot close together on the muscovite MDS configuration (Fig 4.5c). Similarly, the Al/(Fe+Mg+Si) ratios of samples ZL6, Tongbai-Dabieshan and the Jinsha River are all very low, causing this group of samples to plot elsewhere on the MDS map. Finally, XG, and the Xiang and Han rivers and Yichang sample have intermediate Al/(Fe+Mg+Si) ratios which puts them in a third group on the MDS configuration.

4.2 \(^{40}\text{Ar}/^{39}\text{Ar}\) Dating of Muscovite

More than 92% of muscovite grains yield >90% radiogenic \(^{40}\text{Ar}\), indicating that these muscovite grains are not or only marginally altered. The following discussion is confined to those muscovites with a precision of better than 5% for grains older than 20 Ma and <20% uncertainty for grains younger than 20 Ma. Nearly 82% of the detrital muscovite grains from sample ZL1 (~79m) show a continuous distribution between 27 Ma to 153 Ma which is similar to that of the Min River and Yichang (Fig 4.4m & h). In sample ZL2 (~126m) ~86% of the grains plot in the range between 17 Ma and 187 Ma, overlapping with those
of the Yichang sample (Fig 4.4n). Young (<70 Ma) muscovites in samples ZL1 and ZL2 are confined to sediment of the Dadu River. Samples ZL4 (~220m) and ZL5 (~281m) have similar age distributions, suggesting that they have similar source areas. For these two samples, the most significant age cluster is ~90-150 Ma with a peak around 131 Ma, which overlaps with that of the East Min River (Fig 4.4b, o & p). Muscovite ages from sample ZL6 (~300m) are distributed mainly between 100 and 250 Ma, with two major age peaks at 135 Ma and 213 Ma (Fig 4.4q). These two major peaks can be found in the Xiang River sample and Tongbai-Dabieshan bedrock ages. For sample XG, ~61% of the muscovite ages are <250 Ma, with two peaks at 135 Ma and 223 Ma (Fig 4.4r), similar to those of sample ZL6.

In order to constrain the source of the sediments from the ZL and XG cores, we also include published muscovite ages from the potential source areas, including detrital muscovite ages from major tributaries and bedrock ages from the Tongbai-Dabieshan in our study (Fig 4.4). These data are also included in our multi-dimensional scaling model (Fig 4.5a). It is shown that based on $^{40}$Ar/$^{39}$Ar data sample XG is most similar to ZL6. Samples ZL4 and ZL5 are plotted close together with the Xiang and East Min rivers. Sample ZL2 is closer to Yichang sample and sample ZL1 is most similar to the Min River. The muscovite data provide better distinction between Min River and other tributaries as it records recent geological events.

**Figure 4.3** Boxplot for Al/(Fe+Mg+Si) of muscovite from Zhoulao and Xingou cores and major tributaries. The muscovite chemical composition data for the Min, Jialing and Jinsha rivers are from Sun et al. (2016). The reference list for muscovite chemical composition data of Tongbai-Dabieshan (TDS) is given in Appendix 4A. Bars within the boxes represent median values. The bottom and top of the box represents the 25th and 75th percentile, respectively. The bars outside the box represents the 10th and 90th percentiles. Open circles represent outliers.
4.3 Detrital zircon U-Pb ages

In this study, zircon U-Pb ages of >90% concordance were used in the age spectra and MDS plot, that is ~98% of all the dated zircon grains. The zircon data show a wide age range from 3392 Ma to 94 Ma, implying multiple sources and a great variety of rocks in the source areas (Fig 4.6). The common features in the age distributions of the five core samples are peaks around 200-300 Ma, 700-1000 Ma, 1600-2000 Ma and 2000-2400 Ma. However, there are also some differences in the relative heights of these peaks. Samples ZL1-ZL4, and ZL6 have similar age distributions implying that the zircons originate from similar provenance domains or different domains with a similar large scale geological origin.

Figure 4.4 Muscovite $^{40}$Ar/$^{39}$Ar age distribution of sediments from cores and major tributaries. Black lines and gray shade are kernel density estimation (KDE) and probability density plot (PDP) plots. Core and tributaries of the Min River data are from this study. Muscovite ages of the Yangtze tributaries are from Sun et al. (2016). The reference list for the bedrock ages of TDS is given in Appendix 4A.
Although the differences between the detrital zircon age distributions are subtle, their salient differences are reflected in the MDS configuration (Fig 4.5b). For example, the age distributions of the Min, East Min and Dadu rivers all contain the same three age peaks at 200, 800 and 1900Ma. Consequently, these samples all plot in close vicinity to each other on the MDS configuration. And samples ZL1 - ZL4 are all composed of the same four age components at 300, 800, 1900 and 2500Ma and plot together elsewhere on the MDS map. However, because the differences between the age distributions are so small, the MDS configuration is sensitive to random sampling fluctuations. For example, with only 51 grains analysed, it is not possible to reliably constrain the entire age distribution of the Jinsha River, and to precisely compare it to, say, the Min River. The distinction we argue is important for a correct interpretation of these data sets.

5 Discussion

5.1 Sedimentology of core samples

The comparison of the lithological logs of ZL and XG cores and the cross section of Quaternary sediment in the Jianghan Basin allows us to extract general information about the sediment provenance (Fig 4.2). The gravel and sand-gravel deposits between ~50-150m in the XG and ZL cores are generally consistent with a thick gravel and sand interval observed throughout the west part of the Jianghan Basin (Fig 4.2b). This implies that these sediments originate from a source in the west side of the basin, we argue that the most likely source in this area is the upper Yangtze River. The clay and sand layers between ~150-220m in these two cores are also widespread in the west part of the Jianghan Basin, suggesting that these sediments also are derived from the upper Yangtze River (Fig 4.2b). The sand and gravel layers between ~230-280m in the ZL and XG cores are mainly found in the northeast of the Jianghan Basin, implying a main source of sediment supply came from the northeast. Because the cross section only shows the Quaternary sediments in the Jianghan Basin, we cannot shed light on the provenance of sediment deeper than 280m. Note that the combination of the cross section of Quaternary sediment in the Jianghan Basin and lithological logs of ZL and XG cores only provides a first order identification of sediment provenance. More robust evidence about the sediment provenance can be extracted from detrital muscovite and zircon data.

5.2 Provenance of sediments in the cores

We compare sediments from the two cores with modern sediments from the trunk stream or major tributaries to constrain sediment provenance. Ideally, sediments from the cores should be compared with similarly aged sediments. This requires both much more data (this study of 7 cores samples from different ages with 11 tributaries / trunk stream locations would require at least 77 samples to be fully analyzed) and availability of these sediments at different ages. Due to these limitations, we assume that modern sediments represent a good analog to rule out at least some of the tributaries as the major sediment contributor and figure out others as the potential dominant sediment supplier to the Jianghan Basin. We draw our conclusions about the provenance based on the combination of a joint analysis of all our data, including the chemical compositions, the
Samples XG and ZL6 have similar muscovite $^{40}\text{Ar}/^{39}\text{Ar}$ age distributions, comprising of two prominent age components at 150 and 210 Ma and a long tail of Palaeozoic to late Proterozoic ages. This is reflected in their close proximity when plotted in the MDS map (Fig 4.5a). The age distribution and composition of sample XG partially overlaps with the Xiang, Han, Min, Jinsha and Jialing (Figs. 4.3 & 4.4), suggesting that XG may be a mix of sediments from these rivers, although not all of them need to be included to arrive at the observed patterns. We therefore suggest that the sediment in sample XG was potentially derived from a combination of the Xiang, Han, Min, Jinsha and Jialing rivers.

The muscovite and zircon ages and muscovite chemistry reveal that sample ZL6 is markedly different from the samples ZL1-ZL5 (Figs 4.3, 4.4, 4.5 & 4.6). Sample ZL6 resembles the Tongbai-Dabieshan and Han River in Fig 4.5a based on muscovite ages and is closer to the Tongbai-Dabieshan and Jialing River in Fig 4.5b based on zircon ages. The chemical composition data clearly show that sample ZL6 mainly overlaps with the Jinsha River and Tongbai-Dabieshan (Figs. 4.3 & 4.5c). The above discrepancy in muscovite and zircon ages may be explained by difference in geological processes and time scales.

**Figure 4.5** a, b and c) Non-metric multi-dimensional scaling (MDS) plots of muscovite $^{40}\text{Ar}/^{39}\text{Ar}$, zircon U-Pb data and muscovite Al/(Fe+Mg+Si). Solid lines mark the closest neighbours and dash lines the second closest neighbours (based on Vermeesch, 2013). d) “3-way” map combining zircon, muscovite ages, Al/(Fe+Mg+Si) data (based on Vermeesch et al., 2016). Sample ZL3 lacks muscovite ages and samples ZL5 and XG lack zircon ages and are therefore omitted from the “3-way” analysis. e) The source weights, which show the relative important which each of the four proxies attach to the horizontal and vertical axis of the group configuration (Vermeesch et al., 2016). TDS - Tongbai-Dabie Shan.
reflected by U/Pb and \(^{40}\)Ar/\(^{39}\)Ar data and sediment mix. Although the Han and Jialing rivers seem to be reflected in resp. the muscovite \(^{40}\)Ar/\(^{39}\)Ar and zircon U-Pb, the geochemistry clearly shows that the Han and Jialing rivers are at most a minor source of sample ZL6 (Fig 4.3). The combination of muscovite and zircon ages and muscovite geochemistry data suggests that Tongbai-Dabieshan and the Xiang River are the major source areas of sample ZL6. Based on the positions of the Tongbai-Dabieshan, Xiang River and ZL core, we suggest that the Xiang River and a river originated from the Tongbai-Dabieshan (paleo-Han River?) might join with the Yangtze River west of the ZL core locality and deposit sediment at the core location.

The similarity between muscovite geochemistry and age distributions of samples ZL4 and ZL5 implies that they originated from a similar source (Fig 4.4). We do not have zircon U-Pb data from sample ZL5, but the zircon U-Pb age distribution of sample ZL4 is similar to that of the Yichang sample which represents the upper Yangtze River. Detrital muscovite geochronology suggests a dominance of sediment derived from the Xiang River and East Min Rivers and a minor contribution from the Jialing and Zi rivers for ZL4 and ZL5. In contrast, chemical compositions of muscovite grains show that the Xiang River is not the dominant source of these muscovite grains (Figs 4.3 & Fig 4.5c). The similarity in muscovite age distribution and geochemistry of samples ZL4 and ZL5 implies that muscovite grains in sample ZL4 and ZL5 were also dominantly derived from the East Min River. Fig 4.3 shows that part of the muscovite grains from samples ZL4 and ZL5 overlap with the Han, Min and Jialing rivers, suggesting that these rivers might be part of the source of these two samples. We therefore conclude that most of the muscovite grains in samples ZL4-ZL5 were derived from the upper Yangtze River (Min and Jialing rivers) (Fig 4.5d) when it is assumed that the core sediments represent main stream samples and not local/regional tributaries.

Sample ZL2 is similar in zircon and muscovite geochronology to the Yichang sample (Figs 4, 5a-b & 6). This indicates that sample ZL2 was mainly derived from the upper Yangtze River. Some young muscovites (~12%, <70Ma) seem to originate from the Dadu River (Fig 4.4d & n, and Supplementary Fig S.1). Muscovite geochronology suggests that most of the muscovite grains in sample ZL1 were derived from the Min River and Yichang, whereas zircon geochronology indicates a closer affinity to the Xiang River. However, muscovite geochemistry shows that the Xiang River is not the dominant source area of this sample (Fig 4.3). In addition, the muscovite ages demonstrate that the Min River is an important contributor to the muscovites reaching Yichang (Fig 4.4e & h). We therefore conclude that the Min River is the part source of sample ZL1. Fig 4.4a and Supplementary Fig S.1 further show that young muscovite grains (~46%, <70 Ma) in sample ZL1 were derived from the Dadu River. The similar zircon age distributions of the Dadu and East Min rivers prevent us from resolving their respective contributions to samples ZL1and ZL2 (Fig 4.6 and supplementary Fig S.2). This may be due to the closure temperature of zircon being much higher than that of muscovite, causing zircon to be insensitive to the immediate tectonic events of the eastern Tibetan Plateau.

It could be argued that the Min River cannot contribute ~46% muscovites to the Quaternary Jianghan Basin because this river is not a dominant water supplier to the upper Yangtze. However, muscovite \(^{40}\)Ar/\(^{39}\)Ar ages of the modern Yangtze sediment show that
Figure 4.6 Zircon U-Pb age distribution of sediments from cores and major tributaries. Black lines and gray shade are kernel density estimation (KDE) and probability density plot (PDP) plots. Zircon age of tributaries are from He et al. (2014). The reference list for the bedrock ages of Tongbai-Dabieshan (TDS) is given in Appendix 4A.
the Min River is an important sediment supplier to Yichang and the Yangtze delta due to the high erosion rate in the Min River basin (Sun et al., 2016; Hoang et al., 2010). The Min River drains the Longmen Shan and Xianshui He Fault areas that have been already tectonically active since the Miocene (Zhang et al., 2004). Moreover, the exhumation rates of the Longmen Shan and Xianshui He Fault areas inferred from the thermochronometry data are higher than other areas of the upper Yangtze River (Godard et al., 2009; Kirby, 2008; Kirby et al., 2002).

It is not surprising that the MDS plots of zircon and muscovite are not completely identical because muscovite and zircon provide a different window on recent and old geological events. In addition, the discrepancy in transport speed of these two minerals in the Yangtze River due to their distinct density (muscovite: 2.82 g/cm³, zircon: 4.65 g/cm³) and the differences in their hydrodynamic properties could also partly cause the different MDS maps. Furthermore, significant differences between the three MDS maps may arise from the fact that zircon and muscovite are derived from different lithologies and that the zircon and muscovite ‘fertility’ in the different source areas may be significantly different (Moecher and Samson, 2006). Muscovite age and chemistry patterns are clearly distinct in rivers (Dadu and Min rivers) originating from the Xianshuihe Fault and Longmen shan Fault zones when compared with other tributaries (Fig 4.5a). The Jinsha and Min rivers are draining the Songpan-Garze block and the southeastern and eastern Songpan-Garze complex contain sediment derived from the Qinling - Dabie orogen of Middle to Late Triassic age (Enkelmann et al., 2007; Weislogel et al., 2006, 2010). The Jinsha and Min (Dadu and East Min) rivers contain reworked zircon from the Qinling - Dabie orogeny. Consequently, it is not surprising that the Jinsha, Min, Dadu and East Min rivers have similar zircon U-Pb age distributions. The Al/(Fe+Mg+Si) ratios in muscovite suggest that muscovites of samples ZL1, ZL2, ZL4 and ZL5 are similar in composition to those of the Jialing River (Fig 4.5c), which contrasts with inferences drawn from the geochronological provenance proxies (Fig 4.5a & b). We attribute this discrepancy to a wider distribution of metamorphic rocks in the Jialing River drainage basin compared those of other rivers in upper Yangtze River (Fig 4.1b). Based on the Tschermark substitution, muscovite geochemistry is expected to provide greater resolution of metamorphic rocks in the Jialing River than the geochronological methods when the upper Yangtze River was the major source area. The muscovite, zircon ages, Al/(Fe+Mg+Si) proxies are visualized together in Fig 4.5d. Samples ZL2 and ZL4 and Yichang (upper Yangtze) plot together on the group configuration of a 3-way MDS analysis (Fig 4.5d), suggesting that they were derived from the upper Yangtze River. Sample ZL6 originated from the Tongbai-Dabieshan (TDS) (Middle reaches).

5.3 Implications for the evolution of the Yangtze River

5.3.1 Influence of variations in erosion rate on sediment provenance

We observed two significant changes in provenance that can be either related to reorganization of drainage patterns in the Yangtze River and/or to variation in erosion rates in the source area. Our new data suggests that these significant changes occurred at 2.8-2.6 Ma (between ZL6 and ZL5) and 2.1-1.2 Ma (between ZL4 and ZL2). If the erosion
rate significantly increases in a source area, the detrital muscovite age population in stratigraphic sequences in a foreland basin is expected to shift to a younger and narrower age distribution (Whipp et al., 2009). The main difference between ZL6 and ZL5 is that the age population between 200-260 Ma is much smaller in ZL5 than in ZL6 (Fig 4.4p & q). The youngest muscovite age peak center (~140 Ma) in ZL5 and ZL6 is same, implying that the erosion rate in the source area is stable but that part of the sediment provenance changed, which is supported by the remarkably discrepancy in muscovite geochemistry between ZL5 and ZL6 (Fig 4.3). We therefore conclude that the discrepancy in age distribution between ZL5 and ZL6 is not caused by the variation of erosion rate but by sediment provenance changes.

Somewhere between 2.1-1.2 Ma (between ZL4 and ZL2) young muscovite grains (<70 Ma) appear, that seem to be derived from the drainage system of the upper Dadu River (upstream from Shimian). This area experienced rapid exhumation from 13-9 Ma (Fig 4.7), that was accompanied by increased erosion rates, which is much earlier than the occurrence (2.1-1.2 Ma) of these young muscovites in the Jianghan Basin. In addition, we did not find evidence in literature for large scale increases in erosion caused by tectonism or climate change during 2.1-1.2 Ma in the middle and upper Yangtze River drainage system (Fig 4.7). The East Asian winter monsoon significantly intensified since ~3 Ma (An et al., 2001; Clift and Plumb, 2008; Hess and Kuhnt, 2005), which predates 2.1-1.2 Ma interval identified in

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this study. If this change of climate caused clear changes in erosion rates in the source area, this change in erosion rate would have been recorded in previous studies as tectonism (Fig 4.7). Therefore, the remarkable change in age distribution between ZL4 and ZL2 and ZL5 and ZL6 is unlikely controlled by variation in erosion of the source area but by sediment provenance.

5.3.2 Implications for the formation of the Three Gorges

The timing of establishment of a connection between the small local rivers in the Jianghan Basin to rivers in the Sichuan Basin is crucial for understanding the evolution of the Yangtze River. This connection is formed by the Three Gorges where the Yangtze cuts through the Wushan ranges (Fig 4.1a) causing 3 consecutive gorges of ~200km long. Previous studies propose that the formation of the Three Gorges can be dated back to Eocene-Miocene (Richardson et al., 2010; Zheng et al., 2013), Pliocene (Fan et al., 2005) or late middle Pleistocene (Li et al., 2001; Xiang et al., 2007; Yang et al., 2006; Zhang et al., 2008) (Fig 4.8). No consensus exists on the exact timing of the birth of the Yangtze and Red River capture because various methods were used for a range of samples collected in different places (Fig 4.8).

The sediments in sample XG (3.5 Ma) may be derived from Xiang, Han, Jinsha, Min, and Jialing rivers. If the latter three rivers are the source, sediments in this sample came

<table>
<thead>
<tr>
<th>Formation of the Three Gorges</th>
<th>Eocene</th>
<th>Oligocene</th>
<th>Miocene</th>
<th>Pliocene</th>
<th>Quaternary</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>45-40Ma, Richardson et al. (2010)</td>
<td>36.5-23Ma, Zheng et al. (2013)</td>
<td>Before Miocene, Wang et al. (2013)</td>
<td>&gt;3.4Ma, Zhang et al. (2016)</td>
<td>&gt;3.2Ma, La et al. (2010)</td>
</tr>
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<td></td>
<td>&gt;3.4Ma, Zhang et al. (2016)</td>
<td>&gt;3.4Ma, Zhang et al. (2016)</td>
<td>&gt;Quaternary, Shao et al. (2011)</td>
<td>&gt;Early Pleistocene, Fan et al. (2010)</td>
<td>&gt;1.2-1.0 Ma, Gu et al. (2014)</td>
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<tr>
<td></td>
<td>&gt;0.75Ma, Xiang et al. (2007)</td>
<td>&gt;1.18Ma, Yang et al. (2006)</td>
<td>&lt;0.12Ma, Chen et al. (2009)</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>&gt;9 Ma, McPhillips et al. (2016)</td>
<td>&gt;late Miocene, Hoang et al. (2009)</td>
<td>Late Miocene, Wang et al. (2014)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>&gt;34Ma</td>
<td>23Ma</td>
<td>5.3Ma</td>
<td>2.5Ma</td>
<td>0Ma</td>
</tr>
</tbody>
</table>

- **Eocene**: Apatite (U-Th)/He and fission-track
- **Oligocene-Pliocene**: Zircon U-Pb
- **Miocene**: Pb isotope of K-feldspar
- **Pliocene**: Nd isotope
- **Quaternary**: Zircon U-Pb

**Sample site**: Three Gorges, lower Yangtze, Jianghan Basin, Yangtze delta, Jianghan Basin, Yangtze delta, Yangtze delta, South China Sea, upper Yangtze, upper Yangtze, upper Yangtze.

**Methods**: Gravel statistic, Digital elevation model, Heavy mineral, Southsea of the Tibetan Plateau, upper Yangtze, South China Sea, upper Yangtze, upper Yangtze, upper Yangtze.

*Figure 4.8* Various model of the formation time of the Three Gorges and Jinsha River. The above-mentioned references are listed in Appendix 4A. Note. >: no later than, <: no earlier than, *: not provenance study.
from the upper Yangtze River, implying that the Three Gorges already existed around 3.5 Ma or before. If the Xiang and Han river catchments are the sediment source, it is not likely that the Sichuan Basin was already connected to the Jianghan Basin through the Three Gorges at that time. However, Pb isotope data of detrital K-feldspar from the Zhourao and Xingou cores indicate that the upper Yangtze River supplied sediment to the Jianghan Basin before 3.4 Ma (Zhang et al., 2016). We, therefore, suggest that the Jinsha, Min, and Jialing rivers provided sediment for sample XG and that the Three Gorges had already formed at that time (Fig 4.9a). The sediments in sample ZL6 (2.8 Ma) mainly originated from the Xiang River and the Tongbai-Dabieshan north of the core sites, implying one river (paleo-Han River ?) originating from these mountain ranges flowed into center of the Jianghan Basin (Fig 4.9a). These two rivers could join with the Yangtze River west of the ZL core locality at that time, causing that sediment from the upper Yangtze might be diluted by these two rivers.

The inferred formation time of the Three Gorges is consistent with a Pre-Quaternary birth of the Yangtze (Zheng et al., 2013; Richardson et al., 2010; Fan et al., 2005; Shao et al., 2011). However, many previous studies suggest that the Three Gorges section of the Yangtze are younger than 2 Ma (Fig 4.8), which is inconsistent with the current data set and studies mentioned before. Gu et al. (2014), Wang et al.(2009), and Yang et al.(2006) detected a change in sediment provenance in Quaternary sediment in the Jianghan Basin and Yangtze delta using major and trace elements, zircon U-Pb and monazite Th–U–Pb age dating, respectively. (Fig 4.8). We suggest that instead of evidence for the opening of the Three Gorges section, it is more likely that these studies found evidence for the capture event of the Dadu River (2.1- 1.2Ma) (see section 5.3.3).

5.3.3 Implication of the extension of the Min River

As discussed above the young muscovite grains (<70 Ma) in samples Z1 and Z2 must have been derived from the Dadu River. The new source characterized by a 17-70 Ma peak might be caused by the capture of the upper Dadu River by the East Min river in the Sichuan Basin (Fig 9b & c). Muscovites from the upper Dadu River are not detected in samples ZL4 (2.1 Ma) and ZL5 (2.6 Ma), implying that the upper Dadu River (upstream from Shimian, Fig 4.1c) did not flow into the Sichuan Basin and did not transport sediment to the Jianghan Basin before 2.1 Ma (Fig 4.9b). One could argue that the absence of Dadu River muscovites in ZL4 and ZL5 is caused by the dilution from other sources. However, about 46% and 12% of young muscovite grains in ZL1 and ZL2 were derived from the Dadu River. If the absence of the Dadu River muscovite in ZL4 and ZL5 was caused by dilution, it is difficult to explain why ZL1 and ZL2 were not affected by dilution. Instead, we suggest that the Dadu River flowed southward into the Anning River, a current tributary of the Jinsha River, along the Xianshui He Fault at that time (Fig 4.1c). One could argue that young muscovite grains should be observed in ZL4 and ZL5, because the water (and sediment) still arrives in the Jianghan Basin, only the grains were transported over a longer distance (~1800km versus ~1200 km) compared to current course (Fig 4.9b & c). However, these muscovite grains were transported by high velocity water flow in the Anning and Jinsha river valley and might have been abraded into undetectable grains when they arrived into the Jianghan Basin (ZL4-ZL6 and XG) or are a least diluted by other sediment
sources. Nevertheless, the young muscovite grains (<70 Ma) upstream of Shimian appear in samples ZL1 and ZL2, suggesting that the upper Dadu River was captured by the lower Dadu River between 2.1-1.2 Ma (Fig 4.9a & b). This is also supported by the following geomorphological evidence: 1) the presence of a wind gap in the headwater of the Anning River; 2) the occurrence of high bedrock terraces upstream of the wind gap; and 3) the Anning valley being too wide to have been produced by a small river (Clark et al., 2004). This is further supported by evidence that the widespread Dayi conglomerate (burial age of ~2 Ma) in the west of the Sichuan Basin was derived from the East Min and Qingyi rivers and not from the Dadu River (Kong et al., 2011; Li et al., 2007).

Figure 4.9 Proposed model of the Yangtze evolution. The white arrows indicate flow direction.
We attribute this capture event to both tectonism and climate change. Movement along the Xianshuihe strike-slip fault motion (see Fig 4.1c for location) began ~13-10 Ma (Wang et al., 2009b; Zhang, 2013) and caused ~11km left-lateral displacement near Shimian (Zhang, 2013). Fission track data of apatite from samples from near Shimian record a rapid tectonic uplift event since 3 Ma (An et al., 2008). Evidence from the South China Sea, Arabian Sea and Chinese loess shows that strength of the Asia winter monsoon increased since ~3 Ma (An et al., 2001; Clift and Plumb, 2008; Hess and Kuhnt, 2005). The onset of widespread glaciation around 2.7 Ma on the eastern Tibetan Plateau would have caused increased erosion and deposition because glacial erosion rates tend to be higher than fluvial erosion rates (Hallet et al., 1996; Montgomery, 2002). Climate change may have accelerated the extension of the rivers in the Sichuan Basin to the upper Dadu and Jinsha rivers.

Based on changes in sediment provenance in Quaternary sediment in the Jianghan Basin and Yangtze delta, Gu et al. (2014), Wang et al. (2009), and Yang et al. (2006) suggested that the Three Gorges section of the Yangtze formed at some time later than 2 Ma (Fig 4.8). Gu et al. (2014) identified a significant variation in sediment provenance between 1.0-1.2 Ma in the Yangtze delta using major and trace elements and Jianghan Basin. Yang et al.(2006) detected young monazite grains (<25 Ma) that appeared around 1.18 Ma in the Yangtze delta. Wang et al.(2009) observed young zircon (<20 Ma) appeared at some time between 1.2-0.8 Ma in the Jianghan Basin and suggested that the Three Gorges section formed at that time. Instead of evidence for the opening of the Three Gorges section detected in the Jianghan Basin and Yangtze delta, it is more likely that these studies found evidence for the capture event of the Dadu River (~2.1-1.2Ma). These young zircon and monazite grains might be derived from the Cenozoic Gonggashan granite (GSG) in the Dadu River basin (Fig 4.1c). Sediment from the Dadu River was detected in the middle and lower reaches after the capture event due to reduced abrasion of high velocity water flow in the Anning and Jinsha rivers and dilution by rivers with shorter transport distances.

6 Conclusion

Our data provide new constraints on the reconstruction of the Yangtze river system since late Pliocene. One river originating from the Tongbai-Dabieshan north of the Jianghan basin deposited material into the center of the Jianghan Basin during the late Pliocene. We infer that the Three Gorges section of the Yangtze River was formed earlier than ~3.5 Ma. In the early Quaternary (2.6-2.1 Ma), the Qingyi, East Min and Jialing rivers in the Sichuan Basin were the major sediment contributors to the Jianghan Basin. Our data also suggest that the upper Dadu River flowed southward into the Anning River at that time. The originally south flowing upper Dadu River was captured by lower Dadu River during the early Pleistocene (2.1-1.2 Ma) and became one of the major sediment contributors to the Jianghan Basin.
Supporting information

Figure S.1 Muscovite age distributions of sediments from cores and the Min River. All data are also shown in the main text, but here the link between Min river and core data is better visualized.
Figure S.2. Comparison of zircon age distributions from Zhoulao core with the Min River. Black lines and brown shade are kernel density estimation (KDE) and probability density plot (PDP) plots. All data are also shown in the main text, but here the link between Min river and core data is better visualized. Zircon U-Pb data of the Dadu and east Min River from He et al. (2014)
Appendix 4A

The reference list for the muscovite geochemistry of the Tongbai-Dabieshan (TDS).


The reference list for the muscovite bedrock ages of Tongbai-Dabieshan (TDS).


Webb, L.E., Hacker, B.R., Ratschbacher, L., McWilliams, M.O., Dong, S.W., 1999. Thermochronologic constraints on deformation and cooling history of high- and ultrahigh-pressure rocks in the Qinling-Dabie orogen, eastern China. Tectonics 18, 621-638.


The reference list for the zircon ages of Tongbai-Dabieshan (TDS).


References mentioned in Figure. 7:


References mentioned in Figure 8:


delta: Geochemical fingerprints reflecting river connection to the sea. Geomorphology 227, 166-173.


Chapter 5

$^{40}$Ar/$^{39}$Ar mica dating of the “Yangtze gravel” sediments in the mid-lower Yangtze reaches: implications for sediment provenance and development of the Yangtze River

Xilin Sun, Chang’an Li, K.F. Kuiper, Zengjie Zhang, J.R. Wijbrans

Based on: Sun, X.L., Li, C.A., Kuiper, K., Zhang, Z.J., Wijbrans, J. "$^{40}$Ar/$^{39}$Ar mica dating of the “Yangtze gravel” sediments in the mid-lower Yangtze reaches: implications for sediment provenance and development of the Yangtze River”. prepared form for submission to Quaternary sciences reviews.

Abstract

The age and evolution of the Yangtze River has been subject of debate for more than one century. In this study, we combine muscovite and biotite $^{40}$Ar/$^{39}$Ar ages and muscovite geochemistry data of Yangtze gravel sediments in the mid-lower Yangtze River to identify the sediment provenance. The spatial and temporal changes in sediment provenance provide diagnostic information on the evolution of the Yangtze River. The combination of detrital mica ages, geochemistry and depositional ages suggests that the Three Gorges section, one of the key gateways in the modern Yangtze drainage system, formed somewhere between 36.5 Ma and 22.9 Ma which confirms previous work. Further we suggest that the early south flowing Jinsha River in the upper reaches lost its connection with the south flowing Red River before the late Miocene. We propose that the incision of the Three Gorges and the Red River disconnection from the Jinsha River are closely linked to the uplift of the Tibetan Plateau and intensification of southeast Asia summer monsoon.
1 Introduction

The collision of India and Asia has caused the uplift of the Tibetan Plateau and lithospheric extrusion west and east from the central Tibet leading to variation in elevated topography. This emerging topography resulted in changes in atmospheric circulation patterns, external surface processes, climate and drainage patterns. As a result many large rivers in southeast Asia, such as the Yangtze, Red, Yellow, Yarlung Tsangpo, Salween and Mekong rivers, drain the Tibetan Plateau and transport large quantities of debris into the oceans. On the one hand, these rivers play a key role in topography development in competition with internal tectonic processes. On the other hand, the variations in topography can trigger changes in drainage patterns that, in turn, may cause changes in the direction of sediment transport. The Yangtze River is the largest river among these rivers and its formation has been subject of debate for more than one century (Clift et al., 2008; Hoang et al., 2009; Li et al., 2001; Willis et al., 1906). Here we define the Yangtze River as a river that originates from the Kunlun ranges in the Tibet and flows into the East China Sea (Fig 5.1a). This does not necessarily imply that the paleo-Yangtze at any point in time exactly followed the present flow path or drainage system. In fact, there is some consensus that the current Yangtze is the product of amalgamation by capture of at least three rivers, now loosely termed the Upper, the Middle and the Lower reaches of the river, each separated by substantial mountain ranges through which the final river had to cut its path.

An originally southeast to northwest regional gradient in topography was reversed by the collision of India-Asia during Cenozoic (She et al., 2012) leading to the development of the current Yangtze. The formation of the “First Bend” and incision of the Three Gorges are two critical events in the development of the Yangtze River. The formation of the “First Bend” incision caused the upper Jinsha River to lose its connection with the Red River and the incision of the Three Gorges section allowed the middle Yangtze to connect with the upper Yangtze. The formation of the connection between the upper Jinsha River and the mid-lower Yangtze River is regards as the critical step in the development of the modern Yangtze River geometry. No consensus exists on the details and timing of the Yangtze River development. The age of formation of the Yangtze ranges from Eocene (Richardson et al., 2010; Wissink et al., 2016), Miocene (Wang et al., 2014b; Zheng et al., 2013), to early Pleistocene (Fan et al., 2005; Li et al., 2001; Yang et al., 2006; Zhang et al., 2008) and middle Pleistocene (Xiang et al., 2007).

The Yangtze gravel sediments are Cenozoic sediments distributed along the mainstream in the middle-lower reaches (Fig 5.1c). Because the Yangtze gravel sediments are distributed on both banks of the Yangtze river, they have long been considered as a critical carrier of evidence for the development of the Yangtze River. However, until now accurate provenance studies of these sediments is lacking. Constraints on sediment provenance of these Yangtze gravel sediments can shed light on the development of the Yangtze River.

Multiple-proxy, rather than one single-proxy, approaches can provide more reliable information on sediment provenance, by avoiding non-unique and spurious source identification. In this study, we combine muscovite and biotite $^{40}$Ar/$^{39}$Ar ages and muscovite geochemistry to identify sediment provenance of the Yangtze gravel sediments. $^{40}$Ar/$^{39}$Ar
age distribution patterns of biotite and muscovite have been successfully used as a powerful provenance indicator (Clift et al., 2004; Hoang et al., 2010; Najman et al., 1997; Pierce et al., 2014). Muscovite and biotite have lower closure temperatures (350 - 425 °C and 300 - 350°C, respectively (Harrison et al., 2009; McDougall and Harrison, 1999) and are less resistant to physical abrasion and chemical alteration, when compared with for example zircon, which would imply that they have a lower potential of surviving multicycle erosion and deposition. The comparison of muscovite and biotite ages in the Yangtze gravels sediment with those of the various tributaries, in principle, allows us to identify the sources of these sediments. Spatial and temporal changes in sediment provenance in the Yangtze gravel will provide new information on the development of the Yangtze River.

![Image](image.png)

**Figure 5.1** Map showing the sections of the Yangtze gravel sediment in the middle-lower reaches. The red circles represent sample sites for muscovite and biotite samples of the major tributaries from Sun et al. (2016). HLA: Huangling anticline, SXY Fm: Shanxiyao Formation.

## 2 Regional geological setting

The Yangtze River is the longest river draining the Tibetan Plateau with a length of ~6300km. The Yangtze River is conventionally divided into three segments: upper, middle and lower Yangtze (Fig 5.1a). The division between upper and middle Yangtze is near the city of Yichang, Hubei province, whereas the division between the middle
and the lower reaches is near the city of Hukou in Jiangxi province. In the middle-
lower reaches of the Yangtze River, a well-known fluvial succession, the Yangtze gravel
sediment, is distributed north and south of the current streambed of the river from the
Three Gorges area to the delta in the East China Sea (Fig 5.1c). The Yangtze gravel
sediments are well exposed for example at Yichang, Wuhan, Nanjing and are composed of
medium to coarse sand containing, rounded to sub-rounded pebbles or cobbles (Fig 5.1c).

The thickness of the Yangtze gravel sediment is up to 100m in Yichang area,
immediately downstream of the Three Gorges. This Yangtze gravel is divided into a
lower formation, the Yunchi Formation, and an upper unit, the Shanxiyao Formation
(Fig 5.1c) and unconformably overlies the Eocene Pailoukou Formation. We studied
a section with ~3m Pailoukou Formation, ~80m Yunchi Fm and ~20m Shanxiyao
Fm near Yichang. The Pailoukou Fm is dominated by interlayered medium-coarse-
grain sandstone, red siltstone and gray sandstone. The Yunchi Fm consists of thick-
bedded, pebble-cobble sized, yellow-grey gravel beds intercalated with fine-grained
sand layers. The Yunchi Fm is interpreted as the product of a high-gradient braided
river deposition system. The Shanxiyao Fm is mainly composed of grey-yellow cobble
sized gravel beds, with several lenticular sand intervals and has been deposited in a
low-sinuosity, gravel-bed braided river system. The concentration of cobbles in the
Shanxiyao Fm is significantly higher than the Yunchi Fm. The pebbles in the Yunchi and
Shanxiyao Fms are mainly composed of quartz, quartzite and chert (Wang et al., 2014b).

The Yangluo section (~10m) near Wuhan contains two gravel layers interbedded
with one sand layer (Fig 5.1c). The grain size data suggest that the Yangluo gravel is
deposited in a braided river sedimentary environment (Mei et al., 2009). Fossil wood
fragments of Miocene age have been reported (Yang et al., 1998). The electron spin
resonance age of the upper gravel layer is 1.56-1.12 Ma (Mei et al., 2009). The pebbles
of this section are mainly composed of quartzite, chert, gneiss and quartz-sandstone.
The Yangtze gravel sediments near Nanjing (Lingyanshan and Guizishan sections)
predominantly consist of medium sand and sub-rounded pebbles over lain by basalt
lavas (Fig 5.1c). The \(^{40}\text{Ar}/^{39}\text{Ar}\) ages of basalt capping the Lingyanshan and Guizishan
sections are 10.3 \(\pm\) 0.13 Ma and 22.9 \(\pm\) 0.34 Ma, respectively (Zheng et al., 2013).

3 Sampling and analytical methods

3.1 Sample description

In total, 11 medium size sand samples were collected from the middle-lower reaches
of the Yangtze, including 9 samples from the sand layers or sand lenses in the Yangtze
gravel sediments and 2 samples from the modern Yangtze River near Wuhan and Nanjing
(Fig 5.1c). Because medium sized sands are more likely to originate from large and distant
source areas compared to gravels, medium sized sands rather than gravels were collected
from the Yangtze gravel sediments for provenance study. Sample information is given in
Table 5.1. Four fluvial sediments and one lacustrine sediment were collected from the sand
layers or sand lenses of the Yichang section (Fig 5.1c). Sample YC1 was collected from the
Eocene Pailoukou Formation. Samples YC2-YC4 were collected from the medium sand
layers at different horizons of the Yunchi Formation and Shanxiyao Formation. Sample YC5 was collected from the lacustrine sediment at the top of the Shanxiayao Formation. Sample YL-T and YL-B were sampled from the Yangluo section near Wuhan in the western of the Jianghan Basin (Fig 5.1c). Sand samples GZS and LYS were collected from lower reaches of the Yangtze River near Nanjing at the same locations of samples Guizishan and Lingyanshan in Zheng et al. (2013). Sun et al. (2016) published detrital muscovite $^{40}$Ar/$^{39}$Ar ages of major tributaries of the Yangtze River and here we extend our data set include biotite.

Table 5.1. Summary of sample information. Mineral indicates mineral separated for analysis (Ms = muscovite; Bt = biotite)

<table>
<thead>
<tr>
<th>Sample number</th>
<th>Description</th>
<th>Location</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Depositional age (Ma)</th>
<th>Mineral</th>
<th>Reference of depositional age</th>
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<td>Fluvial</td>
<td>Yichang</td>
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<td>111°27′10″</td>
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<td>Xiang et al. (2007)</td>
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<td>111°27′12″</td>
<td>1.15-0.75 Ma</td>
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<td>WH</td>
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<td>30°39′41″</td>
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<td>Wuhan</td>
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<td>114°32′49″</td>
<td>Neogene (20-2.5Ma)</td>
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<td>Yang et al. (1998)</td>
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<td>1.5 - 1.1 Ma</td>
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<tr>
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<td>Modern sediment</td>
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<td>32°10′02″</td>
<td>118°50′05″</td>
<td>-</td>
<td>Ms and Bt</td>
<td>-</td>
</tr>
<tr>
<td>LYS</td>
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<td>Nanjing</td>
<td>32°17′49″</td>
<td>118°53′23″</td>
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<td>Ms and Bt</td>
<td>Zheng et al. (2013)</td>
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<td>118°55′56″</td>
<td>&gt;22.9</td>
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</table>

3.2 Analytical methods

Medium sized (200-500µm) muscovite and biotite grains were separated from samples using standard heavy liquids and magnetic separation techniques at mineral separation laboratory of the Vrije Universiteit Amsterdam. Muscovite and biotite grains were purified under a binocular microscope to remove grains with visible inclusions or alteration due to weathering. Muscovite grains were randomly split into two aliquots: one for electron microprobe (EMP) analysis and the other for $^{40}$Ar/$^{39}$Ar dating. The first aliquot was mounted on double side tape, and cast in epoxy resin, and polished to expose the internal surface for electron microprobe analysis. The geochemistry of muscovites were analyzed by JXA-8530F HyperProbe Electron Probe Microanalyzer at the Electron Microprobe Laboratory, Utrecht University. Wavelength dispersive spectrometers were used with 20 nA beam current and 15 kV accelerating voltage. The contents of Si, Fe, Mg and Al in muscovite in the metamorphic rocks are controlled by Tschermark substitution ($\text{Mg}^{2+} + \text{Fe}^{2+}$)\text{[VI]} + $\text{Si}^{4+}$\text{[IV]} = $\text{Al}^{3+}$\text{[IV]} + $\text{Al}^{3+}$\text{[VI]} (Massonne and Szpurka, 1997). We therefore use the ratio of $\text{Al/(Fe+Mg+Si)}$ to plot multidimensional scaling (MDS) plots and place constraints on sediment provenance in this study.

The biotite and second aliquot muscovite grains were wrapped in 6mm diameter
Al-foil packages and sealed into Al-containers with a diameter of 18.8mm and a depth of 3.3mm for irradiation. The containers were irradiated for 18h in CLICIT Facility in Oregon State University Radiation Center with an in-house standard, Drachenfels sanidine (DRA; 25.52±0.08 Ma) (Wijbrans et al., 1995, calibrated to Kuiper et al., 2008), to measure neutron flux variation (J). Muscovite and biotite $^{40}$Ar/$^{39}$Ar age determinations were performed at the Argon Geochronology Laboratory of the Vrije Universiteit Amsterdam. Single muscovite and biotite grains were loaded into 2mm-diameter hole of a 185-holes copper tray which was baked at 150°C for 24hours in ultra-high vacuum sample house to reduce the absorbed atmospheric Ar. Single grains of standards and samples were fused using a 25W Synrad CO$_2$ Laser Instrument by circling a focused beam of ca 10% of full intensity over each sample position. The sample gas was first purified by a cold trap (-70 °C) to trap volatilities and further purified in a stainless-steel gas purification line using externally heated SAES (Fe-V-Zr alloy) getter material in Inconel tubes, and an NP50 getter as the second stage of purification (AGES facility), or NP10 with an Al-Zr getter element (Helix facility). The Ar isotope composition was analyzed using a ThermoFisher HELIX-MC instrument fitted with 5 dual channel (faraday and CDD) collectors (for the present study the m/e: 40 and 39 beams were measured on the faraday collectors fitted with the new 1013 Ohm resistor amplifiers (Koornneef et al., 2014) or by a Hiden HAL 3F Series 1000 Pulse Ion Counting Triple Filter quadrupole mass spectrometer (AGES, fitted with a pulse counting channeltron detector). Procedural blanks were measured between every four unknowns. The raw data were processed using the ArArCALC2.5 freeware data reduction package (Koppers, 2002).

In order to identify sediment provenance of the Yangtze gravel sediments, we compare our new data with published muscovite geochronology and geochemistry data of the major tributaries (Sun et al., 2016 and Chapter 4). The full dataset includes 1025 muscovite ages, 449 biotite ages and 474 EMP analyses. A first assessment of the data uses the Al/(Fe+Mg+Si) plots and $^{40}$Ar/$^{39}$Ar age probability distributions. However, it is difficult, if not impossible, to understand such “big datasets” without statistical help (sensu Vermeesch and Garzanti, 2015)(Vermeesch and Garzanti, 2015). In a first layer of simplification, we convert each of the raw data (muscovite and biotite $^{40}$Ar/$^{39}$Ar ages and Al/(Fe+Mg+Si)) into a dissimilarity matrix using Kolmogorov-Smirnov statistics. Each of the matrices is then fed into a multi-dimensional scaling (MDS) algorithm to visually produce a two dimensional configuration (Vermeesch, 2013). These MDS configurations allow a graphical assessment of the salient similarities and differences between the samples for each of the three datasets. In a second layer of simplification, we combine two dissimilarity measures (Al/(Fe+Mg+Si) and muscovite $^{40}$Ar/$^{39}$Ar ages) into a single dissimilarity matrix. This matrix is fed into a ‘three-way’ MDS algorithm and visually approximates this matrix with a ‘group configuration’. The ‘group configuration’ shows the (dis)similarities between samples (Vermeesch and Garzanti, 2015). Because samples YC1, YC5, YL-B, YL-T and GZS lack biotite $^{40}$Ar/$^{39}$Ar ages due to a low amount of biotite, biotite data are not included in the ‘three-way’ analysis.

The muscovite geochronology and geochemistry data show that the Yangtze River gravel sediments is best interpreted as a mix of sediments from different source areas (see section 4). The comparison of muscovite and biotite data between pre-recent samples and
major tributaries allow us to identify which of the tributaries potentially can be considered as the dominant sediment supplier. In an attempt to model the source mix of the Yangtze gravel, we mix each of muscovite ages and geochemistry data of those potential source areas to represent the source area before formation of the Three Gorges and the Red River capture event. For instance, the Han, Zi and Xiang rivers are the potential source areas to the Yangluo section before the formation of the Three Gorges. We then mix each of muscovite ages (in a ratio of 27:27:40) and geochemistry data (20:18:20) of these areas to present the features of sediments reaching the Yangluo section before the Yangtze cut through the Three Gorges.

4 Results

4.1 Microprobe analysis

About twenty muscovite grains per sample were analyzed by electron microprobe apart from samples YC1 (6 grains) and YC5 (15 grains) that had very low muscovite concentrations. Most of the muscovite grains in the samples YC2, YC4 and YC5 display similar chemical compositions and overlap well with the Qingyi, Min and Dadu rivers in the upper Yangtze, implying that these rivers are the potential sediment sources (Fig 5.2a). Consequently, these samples plot together on right side of MDS map (Fig 5.3c). Muscovite geochemistry data of sample YC1 are different from those of samples YC2-YC5 and partly overlap with East Min River (Fig 5.2a).

The prominent discrepancy in muscovite geochemistry between samples YL-B and YL-T implies that they have different sources. Sample YL-B contains a signal that points to a provenance from the Dabieshan based on muscovite geochemistry. Sample YL-T overlaps with the Han, Xiang and Zi rivers and Wuhan and Mix2 (Fig 5.2b), implying that this sample is a mix of sediment from the Han, Xiang and Zi rivers. Artificial Mix2 is a mix of muscovite geochemistry data for muscovites originating from the Han, Xiang and Zi rivers. The Gan, Han, Xiang and Zi river signals and that for the Dabieshan only partly overlap with the wide range of Al/(Si+Mg+Fe) ratios of samples GZS and LYS, suggesting that sediments in these two fluvial samples may be a mix of sediment from these regions (Fig 5.2b).

4.2 $^{40}$Ar/$^{39}$Ar single-grain dating

In total, 575 muscovite grains and 421 biotite grains were dated in this study. Samples YC1, YC3, YC5, YL-B, YL-T and GZS yielded insufficient biotite for $^{40}$Ar/$^{39}$Ar dating. Published muscovite $^{40}$Ar/$^{39}$Ar ages from the major tributaries and the Dabieshan were also included for comparison.

4.2.1 Yichang section

Thirty-six muscovite grains from the oldest sample YC1 (Eocene) yielded a dominant age peak around 230 Ma (86%) which is consistent with a contribution expected for the Jialing River (Fig 5.3a). Samples YC2 - YC3 show similar muscovite age distributions, which implies that they have similar sources. Muscovite ages of these two samples are composed by two major age clusters of 140-220Ma and 660-800Ma that partly overlap
Figure 5.2 The muscovite geochemistry data. a) comparison of the Yunchi section with tributaries in the upper reaches. b) Yangluo and Nanjing sections are compared with the tributaries in the mid-lower reaches. Mix1 = Qingyi + East Min + Jialing (in a ratio of 22 : 20 : 20); Mix2 = Xiang + Zi + Han (20 : 18 : 20); Mix3 = Xiang + Zi + Han + Dabieshan + Gan (20 : 18 : 20 : 46 : 20). The muscovite geochemistry data of the Min, Jinsha and Jialing rivers and Yichang are from Sun et al. (2016). The muscovite geochemistry data of the Dabieshan and the Zi, Xiang and Han rivers from the Chapter4 (Appendix 4A). Bars within the boxes represent median values. The bottom and top of the box represents the 25th and 75th percentile, respectively. The bars outside the box represents the 10th and 90th percentiles. Open circles represent outliers.
with those of the Jialing, East Min and Qingyi rivers. These samples thus plot in close vicinity to each other on the MDS map (Fig 5.3b). Samples YC4 and YC5 both have a major muscovite age peak around 120 Ma, which can be found in the East Min River and the Yichang samples. These two samples plot close together on the MDS map (Fig 5.3b). About 95% dated biotite grains in sample YC-2 fall in the age range of 0-120 Ma, with a prominent peak at 37 Ma (Fig 5.4a). This signal can be found in the Jialing, Jinsha and Dadu rivers. Biotites from sample YC4 are mainly distributed between 10-102 Ma, with a major peak at 100 Ma, which partly overlaps with the Jialing, Jinsha and East Min rivers.

4.2.2 Yangluo section

Samples YL-B and YL-T were collected from one outcrop and yield different age distributions. Fifty-seven muscovite grains from sample YL-T yield a widespread age range from 104 Ma to 840 Ma, with two major age peaks at 140 Ma and 230 Ma. These two age peaks are observed in the Xiang, Zi and upper Yangtze (Yichang) rivers, which likely reflect sourcing from a mix of sediments from these rivers. Consequently, this sample plots close with Mix2 and Xiang River on the MDS configuration. In contrast, sample YL-B shows a good similarity in muscovite age with data of the Dabieshan and Zi River, suggesting that the sediment in this sample was mainly derived from these two regions.

4.2.3 Nanjing section

Samples GZS and LYS yielded similar muscovite age distributions, implying that they originated from similar sources. The major age clusters of 180-260 Ma and 200-280 Ma are similar to those of the Gan and Xiang rivers and of the Dabieshan (Fig 5.4b). Samples GZS and LYS also partly overlap with those of the Wuhan (WH) and Nanjing (NJ) samples in muscovite ages, but they lack muscovites younger than 60 Ma. Fifty biotite ages of sample LYS fall in a narrow age cluster of 26-38 Ma (Fig 5.4a), implying that they originated from relatively uncomplicated source. The GZS and LYS are plotted close together with the Dabieshan and Mix3 on the MDS map due to their similar muscovite age distributions (Fig 5.5d).

4.2.4 Modern sediment

Samples WH and NJ were collected from the main stream of the Yangtze River with ~600 km apart and yield similar muscovite and biotite age distributions (Figs 5.4b). Most of the muscovite grains in samples WH and NJ are younger than 100 Ma, accounting for ~71% and ~67% of total dated grains, respectively. About 82% of dated biotites in these two samples are younger than 10 Ma (Fig 5.4a).

5 Discussion

5.1 Sediment provenance

5.1.1 Factors influencing age patterns and potential scenarios

Conventionally, pre-recent sediment samples are compared with provenance data from modern sediments collected in the major tributaries or mainstream to define the sediment provenance (Clift et al., 2008; Hoang et al., 2009; Kong et al., 2009; Zheng et al., 2013).
Figure 5.3 Comparison of muscovite age distributions between Yichang and potential source. a) Muscovite age distribution of the Yichang section. Black lines and shaded areas are kernel density estimation (KDE) and probability density plot (PDP) plots. Mix1=East Min+Qingyi+Jialing +Jinsha (in a ratio of 30:30:32:61). b, c and d) Non-metric multi-dimensional scaling (MDS) plots of muscovite $^{40}\text{Ar}^{39}\text{Ar}$ and Al/(Fe+Mg+Si) and biotite $^{40}\text{Ar}^{39}\text{Ar}$ data. The solid lines mark the closest neighbors and dash lines the second closest neighbours (based on Vermeesch, 2013). e) INDSCAL map combining muscovite age and geochemistry (based on Vermeesch et al., 2016). Samples YC1, YC3 & YC5 lack biotite ages and are therefore excluded for the INDSCAL analysis. Mix1=Qingyi+East Min+Jialing+Jinsha
Figure 5.4 Comparison of biotite and muscovite $^{40}\text{Ar}/^{39}\text{Ar}$ age distributions of “Yangtze gravel” and major tributaries. a) Biotite age distributions. Black lines and shaded areas are kernel density estimation (KDE) and probability density plots (PDP). b) Muscovite age distributions of samples from middle-lower reaches. Black lines and shaded areas are kernel density estimation (KDE) and probability density plots (PDP). Mix2 = Xiang+Zi+Han (in a ratio of 40 : 27 :30); Mix3 = Xiang+Zi+Han+Gan+Dabieshan (40 : 27 :30 :39 : 64). The reference list for the bedrock ages of Dabieshan is given in Appendix 5A.
Figure 5.5 The MDS and INDSCAL plots of Yangluo and Nanjing sections. a-b and d-e) Non-metric multi-dimensional scaling (MDS) plots of muscovite $^{40}\text{Ar}/^{39}\text{Ar}$ and Al/(Fe+Mg+Si) data. The solid lines mark the closest neighbors and dash lines the second closest neighbours (based on Vermeesch, 2013). c and f) “3-way” map combining muscovite age and geochemistry (based on Vermeesch et al., 2016). Samples YL-B, YL-T & GZS lack biotite ages and are therefore excluded for the “3-way” analysis.

Ideally, the >22.9 - 0.7 Ma Yangtze gravel sediments should be compared with similar aged sediments upstream to define their source river. This is potentially problematic as it requires both much more data (this study of 9 Yangtze gravel sediments with different depositional ages with more than 10 tributaries / mainstream locations would require at least 90 samples to be fully analyzed) and availability of these sediments at different ages. Bearing these limitations in mind, we introduce as simplification that we may assume that modern sediments represent a good analog to rule out at least some of the tributaries as
the major sediment supplier and identify others as potential dominant sediment supplier to the Yangtze gravel sediments. Since cooling and exhumation are often episodic processes, rather than continuous processes (e.g. Carrapa et al., 2003), in such cases the difference between modern and ancient river sand compositions may not be all that large over time spans of several tens of millions of years. Sun et al. (2016) suggest that the transport of medium sized (200-500µm) muscovite grains in the Yangtze River is not significantly affected by human activity because these minerals are transported as bed load and take a longer time (>1000 years) to travel from source to delta. The potential biases that underlie our approach should be kept in mind when interpreting various provenance scenarios. Note that this is not only valid for this study, but also most previous work.

The muscovite age distributions of samples from the Yangtze gravel sediments are significantly different from the mainstream of Yangtze River (Yichang, Wuhan and Nanjing) due to the presence of young (<60Ma) muscovite grains in the latter (Figs 5.3 & 5.4). Comparison of mainstream (Yichang, Wuhan and Nanjing) and major tributaries suggests that the young muscovites in the mainstream primarily originate from the Dadu River, a current tributary to the Min River (Figs 5.3 & 5.4). Five scenarios could result in absence of these young muscovites in Yangtze gravel sediments (Table 5.2): 1) lack of a gateway (i.e. the Three Gorges) between the upper Yangtze (including Dadu) and the middle and lower reaches; 2) Three Gorges already existed, but the Dadu river flowed southward into the Red River instead of eastward to the middle and lower reaches; 3) The Dadu River transported sediment to the mid-lower Yangtze, but the young bedrocks in the Dadu River basin providing the young muscovite grains (<60 Ma) were not exhumed to surface; 4) The Dadu River transported sediment to the mid-lower Yangtze, but the biotite and muscovite grains did not survive the long traveling distance and 5) Alternatively, the young muscovite and biotite grains originate from a source unidentified by us and other studies. This option will not be further discussed in this study.

Scenario 1

The upper Yangtze cannot be the source of the Yangluo section in the first scenario (the Three Gorges did not form), so this section must be supplied by the Han and/or Xiang and/or Zi rivers. The Jianghan basin, Gan River, Dabieshan area are the potential source areas for the Nanjing sections. The source area for the Yichang section must be local drainage areas near the Three Gorges. Limestone is the dominant rock type in the Three Gorges and will provide only limited micas (from metamorphic, magmatic rocks or sandstone, not from carbonate) to the middle-lower reaches. The crystalline rocks in the core of the Huangling anticline (HLA) include the Archaean-Palaeoproterozoic Kongling complex and Neoproterozoic Huangling granite rocks (Fig 5.1c). Because the Huangling anticline is close to the Yichang section (~60km), the Huangling granite is an important potential source to this section (Fig 5.1c). Biotite of the Huangling granite is at 780-789 Ma (Li et al., 2002) using K-Ar and 829-838 Ma using $^{40}$Ar/$^{39}$Ar dating (Li et al., 2007). These age ranges are observed in the muscovite age distributions of sample YC2 in the Yichang section but not for YC3-YP5 and YC1(Fig 5.3a).
Table 5.2. Potential source areas for different sections according to different scenarios of formation of the Yangtze

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Potential source</th>
<th>Yichang section</th>
<th>Yangluo section</th>
<th>Nanjing section</th>
</tr>
</thead>
<tbody>
<tr>
<td>1: Three Gorges does not exist</td>
<td>Three Gorges area</td>
<td></td>
<td>Dabieshan, Three Gorges areas and Han, Zi and Xiang rivers</td>
<td>Dabieshan, Three Gorges areas and Gan, Han, Xiang, and Zi rivers</td>
</tr>
<tr>
<td>2: Three Gorges exists; Dadu flows S into the Red River</td>
<td>Jialing, East Min and Qingyi rivers and Three Gorges area</td>
<td></td>
<td>Jialing, East Min, Qingyi, Xiang, Zi and Han rivers and Dabieshan</td>
<td></td>
</tr>
<tr>
<td>3: Three Gorges exists; Dadu flows east, young rocks in the Dadu drainage not exhumed</td>
<td>Current upper Yangtze River</td>
<td></td>
<td>middle and upper Yangtze River</td>
<td>all Yangtze River basin</td>
</tr>
<tr>
<td>4: Three Gorges exists; Dadu flows east, young rocks in Dadu drainage exhumed, but micas do not travel far enough</td>
<td>upper Yangtze River, but young muscovite (&lt;60 Ma) absent</td>
<td>middle and upper</td>
<td>Yangtze River but young muscovite (&lt;60 Ma) absent</td>
<td>all Yangtze River basin but young muscovite (&lt;60 Ma) absent</td>
</tr>
</tbody>
</table>

Scenario 2

The Dadu River flows southward into the Red River and the Three Gorges already existed in the second scenario. Given the geographical position of the Jinsha river west of the Dadu river, a connection between the Jinsha River and the Sichuan Basin when the Dadu River flowing southward into the Red River (Fig 5.1a) would be impossible (Fig 5.1a). In addition to the Three Gorges region, also the rivers (Jialing, East Min and Qingyi rivers) in the Sichuan Basin are a potential source to middle-lower reaches. The remarkable muscovite age population at 700-760 Ma of the Qingyi River could be an important indicator for sediment from upper Yangtze River (Fig 5.3a). This age peak overlaps well with the main age peak of samples YC2 and YC3 in the Yichang Section. In addition, the biotite cooling ages of the Huangling granite are between 780 – 789 Ma and 829 – 838 Ma and older than the main muscovite age peak of the Qingyi River. Therefore, presence of muscovites with ages between 700-760 Ma in the Yangtze gravel sediments can be taken to indicate that the Three Gorges were already present.

Scenario 3

In this scenario, we assume very recent exhumation of young rocks in the Dadu drainage system. From all sampled major tributaries only the Dadu River has muscovite grains younger than 60 Ma except one grain from the Jinsha River (1 of 61) (Figs 5.3 & 5.4). The timing of exposure of young bedrocks (\(^{40}\text{Ar}/^{39}\text{Ar}\) ages < 60 Ma) in the Dadu River drainage basin is relevant for this scenario. We further constrain the source of these young muscovites based on literature: muscovites younger than 20 Ma dominantly originate from the Gonggashan granite (Zhang et al., 2004) and muscovite grains between 20 Ma and 80 Ma are mainly derived from the Danba region (Itaya et al., 2009) (Fig 5.6a). Previous
studies have calculated river incision rates near the Danba and Gonggashan regions (Clark et al., 2005; Ouimet et al., 2010). We assume that the exposure time is 0 Ma at the bottom of river valley. The exposure time (T) of a certain elevation at these two transects can be calculated using:

\[ T = \sum_{k=1}^{n} \left( \frac{H_k - H_{(k-1)}}{e_k} \right) \]

where \( H_k \) and \( H_{(k-1)} \) are the elevations of different locations (\( H_k > H_{(k-1)} \)), and \( e_k \) is the incision rate from \( H_{(k-1)} \) to \( H_k \). Based on this equation and the river incision rates at Danba region (~0.33km/m.y for 2.1-3.0km and 0.038 km/m.y for 3.0-3.7km) and Gonggashan (0.1-0.5km/m.y for 1.1-2.6km) calculated from the apatite (U-Th)/He ages (Clark, 2003; Clark et al., 2005; Ouimet et al., 2010), the exposure time is >~18.5 Ma at 3700m for the Danba region and ~15-2.9 Ma at 2600m for the Gonggashan granite (Fig 5.6b & c). Therefore, if the depositional age of a sample is younger than ~18.5 Ma in the mid-lower Yangtze, as is the case for most of the Yichang samples immediately downstream of the Three Gorges (see table 5.1), these young (<60 Ma) muscovite grains can be an indicator for the formation of the Three Gorges and connection of the Dadu River to the Sichuan Basin.

Figure 5.6  a) Compilation of muscovite and biotite \(^{40}\text{Ar}/^{39}\text{Ar}\) ages of the Danba and Gonggashan regions. b) and c) The exposed time of the Danba and Gonggashan regions calculated from the transect apatite (U-Th)/He data. The location of a is shown in the Fig 5.1c.
Scenario 4

In the fourth scenario, we assume that muscovite and biotite grains from the young rocks in the Dadu River have traveled longer distances compared to its current course. It is known that the Dadu River originally flowed southward into the Anning River, a current tributary of the Jinsha River, along the Anning He Fault (Clark et al., 2004). Under this scenario, these muscovite and biotite grains were transported by high velocity water flow in the Anning and Jinsha river valley and as a result might have been abraded into undetectable grains at the time that they arrived into middle-lower reaches or that they were at least substantially diluted by other sediment sources. The rivers in the Sichuan Basin then captured the south flowing Dadu River to form the current course. The transport distance of these young muscovite and biotite grains was shortened more than 600km after this capture event. As a results, these young muscovite and biotite grains in the current course of the river were not exposed to the extreme abrasion of high velocity water flow in the Anning and Jinsha river valley.

5.1.2 Provenance of the Yichang section

Although the muscovite age distributions of sample YC1 is similar to the Jialing River (Fig 5.3), the muscovite geochemistry data show that the YC1 is different from the Jialing River (Figs 5.2a & 5.3c). Moreover, no muscovite grains from the Qingyi River is observed in this sample. We therefore suggest that sediment in sample YC1 was not derived from the Jialing River but instead from local sources (scenario 1 in table 5.2) (Fig 5.7).

The similarity in muscovite ages between YC2 and YC3 implies that they have similar sources. But the muscovite geochemistry data imply that YC3 has more complexities in its source areas than YC2. The overlap between the Qingyi River and samples YC2 - YC3 in muscovite ages suggests that some sediments in these two samples were derived from this river (Fig 5.3a). Some older muscovite grains (>760 Ma) in the YC2 are likely to be derived from the Huangling granite. Muscovite geochronology and geochemistry data imply that part of the some sediment in sample YC2-YC3 might originate from the East Min, Jialing and Jinsha rivers (Figs 5.2 & 5.3). Consequently, we infer that these two samples originated from a mix of sediments from the Qingyi, East Min, Jialing and Jinsha rivers and Huangling granite. This conclusion is further supported by similarity in muscovite age and geochemistry data between these two samples and Mix1 (Figs 5.2 & 5.3). Here Mix1 is a mix of muscovite ages and geochemistry data of the Jialing, East Min, Qingyi and Jinsha rivers (mix ratio given in Figs 5.2 & 5.3) to represent similar aged sediment from the upper Yangtze (Figs 5.2a & 5.3). Therefore, we suggest that YC2 and YC3 are dominantly derived from the Jialing, Qingyi, East Min and Jinsha rivers. The muscovite age distributions of samples YC4 and YC5 overlap with the Jialing and East Min rivers (Fig 5.3a). The biotite ages of YC4 partly overlap with the Jialing, East Min, Jinsha and Dadu rivers. However, the muscovite geochemistry of YC4 and YC5 is remarkably different from that found for muscovites originating from the East Min River, implying that the East Min River is at most a minor source for YC4 and YC5. This mismatch between geochronology and geochemistry in provenance may be caused by the difference in number of analyzed grains (muscovite age n=39 & 47 and geochemistry n=21 & 15) for sample YC4 and
YC5. For muscovite age and geochemistry, there is 95% chance (geochemistry n=15) that at least one fraction ≥10% of the population is missed compared with 14% chance of geochronology (n=39) (Vermeesch, 2004). Therefore, the muscovite geochronological data representing the larger sample are more reliable compared geochemistry data and YC4 and YC5 dominantly originated from the Jialing and East Min rivers with minor from the Jinsha and Qingyi rivers.

The most important changes in sediment provenance of the Yichang section took place somewhere between sample YC1 (Eocene) and YC2 (1.15-0.75 Ma). The source area of this section expanded from a local source of the three Gorges (YC1) to a more regional source in the Sichuan Basin (YC2). The Qingyi River is an important sediment supplier to YC2 and YC3 but a minor sediment supplier to YC4 and YC5. We attribute this variation to sediment dilution from the Jialing, East Min River and Jinsha rivers due to expansion of their river watershed.

5.1.3 Provenance of the Yangluo and Nanjing sections

The prominent discrepancy in muscovite age and geochemistry between YL-T and YL-B implies that they originate from different source areas (Figs 5.2b & 5.4b). The YL-B is similar to the Dabieshan and the Zi River in muscovite ages, but the remarkable difference in muscovite geochemistry between YL-B and Zi River suggests that the Zi River is not the dominant sediment supplier to this sample (Fig 5.2b). Moreover, if the Zi River provided sediment to this sample, it is difficult to explain why the nearby Xiang River did not provide sediment to sample YL-B (Fig 5.1c). Therefore, the similarity in muscovite age and geochemistry between the Dabieshan and YL-B indicates that the Dabieshan is the dominant supplier of sediment to YL-B sample location. This is also reflected in the close proximity of muscovite and Al/(Si+Mg+Fe) on the MDS maps (Fig 5.5a-b). The muscovite ages distributions of sample YL-T overlap with those of the Xiang, Han and Zi rivers, upper Yangtze (Yichang) and Dabieshan, which implies that these areas are the potential sources (Figs 5.4 &5.5a-b). Muscovite geochemistry data show that the Dabieshan is not a main sediment supplier to this sample (Fig 5.2b). Both the muscovite age and geochemistry data show that YL-T is likely to be a mix of sediments from at least the Xiang, Han, Zi and upper Yangtze rivers (Figs 5.4b & 5.5a-b). We therefore suggest that the source areas of sample YL-T was mainly located in the Xiang, Han and Zi drainage system (Fig 5.7).

The similarity in muscovite chronology and geochemistry data between samples GZS (>22.9 Ma) and LYS (>10.3 Ma) suggests that they have a comparable sediment source (Figs 5.4b & 5.5). Because the young rocks in the Dadu River basin were exhumed to the surface before ~18.5 Myr ago (Fig 5.6b), it is not surprising that these young muscovites (<60 Ma) were not observed in sample GZS (>22.9 Ma). Samples GZS and LYS overlap with the Zi, Xiang and Gan rivers and Dabieshan in muscovite age distributions (Fig 5.4b), implying that those muscovite grains originated from those regions. This is consistent with the results of the muscovite Al/(Si+Mg+Fe) ratio (Fig 5.2b). Muscovite geochronology and geochemical data of samples GZS and LYS suggest that at least the current mid-lower reaches of the Yangtze River are the dominant source to the Guizishan (GZS) and Lingyanshan (LYS) sections. Four muscovite grains in samples GZS and LYS fall in the
<table>
<thead>
<tr>
<th>Sample number</th>
<th>Age</th>
<th>Major supplier</th>
<th>Minor supplier</th>
<th>Scenario</th>
<th>Locality</th>
</tr>
</thead>
<tbody>
<tr>
<td>YC1</td>
<td>Eocene</td>
<td>Eastern Three Gorges</td>
<td>×</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>YC2</td>
<td></td>
<td>Qingyi, Jialing and East Min</td>
<td>Jinsha</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>YC3</td>
<td></td>
<td>Jialing and East Min</td>
<td>Qingyi and Jinsha</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>YC4</td>
<td>1.15-0.75 Ma</td>
<td>Jialing and East Min</td>
<td>Qingyi and Jinsha</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>YC5</td>
<td></td>
<td>East Min</td>
<td>Jialing and Qingyi</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>YL-B</td>
<td>Miocene</td>
<td>Dabieshan</td>
<td>×</td>
<td>2/3</td>
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<tr>
<td>YL-T</td>
<td>1.1-1.5 Ma</td>
<td>Han, Xiang and Zi</td>
<td>Jialing, Min and Jinsha</td>
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<tr>
<td>GZS</td>
<td>&gt;22.9 Ma</td>
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<tr>
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<td>&gt;10.3 Ma</td>
<td>Dabieshan, Gan, Han, Xiang and Zi</td>
<td>Qingyi, Min and Jialing</td>
<td>2</td>
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</tr>
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</table>

Figure 5.7 Summary of the sediment provenance of the Yangtze gravel sediments. The solid black lines or black areas indicate the major sediment suppliers. The gray black lines indicate minor sediment suppliers. The dash lines represents non-suppliers. The shaded area represents the Three Gorges region. Number 1 - 4 indicate scenarios discussed in the Table 5.2. Circles indicate sample locations. DBS: Dabieshan.

age cluster of 700-760 Ma, the dominant age population of the Qingyi River, implying that the Qingyi River supplied minor sediment to these two sections. Because muscovite grains with ages of 700 - 760 Ma are not observed in samples from major tributaries in the middle lower reaches (Fig 5.4b), these muscovite grains in these two samples are unlikely to be derived from the middle lower reaches. Therefore, the source areas of samples GZS and LYS are at least the mid-lower Yangtze River and rivers in the Sichuan Basin (East Min, Qingyi and Jialing rivers).

5.1.4 Comparison between Yangtze gravel and Zhoulao and Xingou cores

The upper stream of the Yangtze provided sediment to the Yichang and Yangluo sections in the Jianghan Basin. Provenance signals of the upper Yangtze will be recorded in both the Yangtze gravel sediments and sediment in the depocenter of the Jianghan Basin.
Therefore, the muscovite age distributions of the Yichang and Yangluo sections can be directly compared with those of samples from the Zhoulao and Xingou cores (discussed in chapter 4) in the depocenter of the Jianghan Basin. Fig 5.8 shows that muscovite age distributions of samples YC2 and YC3 are similar to those of sample XG (~3.5 Ma). Sample YC4 has similar muscovite age pattern when compared to that of sample ZL4 (~2.1 Ma) and ZL5 (~2.6 Ma). Xiang et al. (2007) suggest that the electron spin resonance ages of the Yichang section are between 1.15 Ma and 0.75 Ma. Comparison of the muscovite age patterns between Yangtze gravel sediments and core sediments implies that the depositional ages of YC2-YC5 are ~3.5 - 1.2 Ma and older than ESR ages of 1.15 - 0.75 Ma. This mismatch might be due to the fact that samples YC2-YC5 are older than the range of applicability of ESR dating (a few thousand years to 1-2 Ma (Grün, 1993)). Alternatively, the age models of the 2 sediment cores based on magnetostratigraphy might be inaccurate. Because the Yangtze gravel sediments at Nanjing (>10.3 Ma) are much older than sediments from the Zhoulao and Xingou cores, they cannot be compared with the latter.

5.2 Implications for the development of the Yangtze River

5.2.1 The formation of the Three Gorges

The absence of sediment from the Sichuan Basin in YC1 (Eocene) located just downstream of the Three Gorges implies that the middle Yangtze River did not incise the Three Gorges area during the Eocene. The presence of several kilometers thick hydrocarbon-bearing shale and evaporite deposits in the Jianghan Basin of 56 Ma – 36.5 Ma also precludes the routing of a large river system like the Yangtze River through the Jianghan Basin before 36.5 Ma (Zheng et al., 2013 and references therein). These sediments exclude the existence of a large river that provides a large amount of water discharge and sediment flux into the Jianghan Basin at that time. The depositional ages (56 Ma - 36.5 Ma) of hydrocarbon-bearing shale and evaporite deposits are constrained by K-Ar ages of interbedded basalts in the Jianghan Basin. These ages are generally consistent with the age-depth relation in the Eocene – Paleocene sediments, implying that these ages are reliable. The supply of sediment from the Jialing, Qingyi and East Min rivers to YC2 & YC3 (1.15-0.75 Ma) suggests that the Three Gorges have formed at least before 1.3 Ma. Therefore, our data from Yichang section provide a first order constraint on the formation time of the three Gorges somewhere between 36.5-1.3 Ma.

For the Yangluo section we determined the provenance for two samples: stratigraphically the lowest (and oldest) sample (YL-B) reflects a local sediment source and does not reveal if the Three Gorges existed or not. The younger sample (YL-B) shows a sediment signature for upper Yangtze demonstrating the Three Gorges did exist at that time. The depositional age of these two samples is however controversial. Mei et al., (2009) suggested that the electron spin resonance (ESR) ages of upper part of the Yangluo section are 1.56-1.12 Ma. Chen and Ma (1987) suggest that the lower part of the Yangluo section belongs to the Miocene and the upper part to the Pleistocene. Based on these studies and significant discrepancy in sediment provenance between YL-B and YL-T, we suggest that the YL-T sample belongs to the Pliocene - Quaternary and YL-B belongs to the Miocene.
**Figure 5.8** Comparison of muscovite ages distributions between the Yangtze gravel sediments and Zhoulao and Xingou cores in the Jianghan Basin.
Although the muscovite age and geochemistry data suggest that the mid-lower reaches of the Yangtze are the most important source area for samples GZS (>22.9 Ma) and LYS (>10.3 Ma) from the lower reaches, both samples contain a minor component of sediment from the Qingyi River. This implies that the Yangtze River already incised the Three Gorges at that time and transported sediment from the Sichuan Basin to the lower reaches before 22.9 Ma. The radio-isotope age constraints based on the $^{40}\text{Ar}/^{39}\text{Ar}$ data from basalts capping the sections seem reliable: plateau and isochron ages are consistent and radiogenic $^{40}\text{Ar}$ yield is high (>80%) (Zheng et al., 2013). The combination of evidence from the Yichang, Yangluo and Nanjing sections suggests that the Three Gorges formed between 36.5 Ma and 22.9 Ma (Fig 5.9). This is supported by detrital zircon U-Pb data from the Yangtze gravel sediments at Nanjing (Zheng et al., 2013). Moreover, this age 36.5 - 22.9 Ma for the Three Gorges is also consistent the Nd isotopic data from the Red River system which indicates that the Red River lost connection with the rivers in the Sichuan Basin during Oligocene (Clift et al., 2006).

Figure 5.9 The evolution of the Yangtze River based on the Yangtze gravel sediment. The white arrows indicate flow direction.

Richardson et al. (2010) suggested that the Three Gorges formed before 40 Ma based on a rapid cooling event (~40 Ma) recorded by apatite (U-Th)/He data from a vertical profile at the Three Gorges, which disagrees with our 36.5 - 22.9 Ma formation time of the Three Gorges. The closure temperature of apatite (U-Th)/He is ~70 ℃ that is 2 km below the surface if a constant 30 ℃ /km geothermal gradient and 10 ℃ surface temperature are assumed (Garzione, 2008). Consequently, these apatite grains were located at least 2 km below surface when they passed through their closure temperature at 40 Ma. Although the exact exhumation time is unclear, the formation of the Three Gorges is likely to be younger than 40 Ma. Moreover, the presence of ~2 km of evaporites in the Jianghan Basin (56 - 36.5 Ma) (Zheng et al., 2013) also suggests that a large river flowing across the Jianghan Basin is unlikely to exist before 40 Ma.
5.2.2 The extension of the Jinsha River

Because sediment provenance from the Jinsha River was not clearly detected in the GZS and LYS, it is not clear whether the Jinsha River was connected to Sichuan Basin before 22.9 Ma from our data. Detrital zircon U-Pb data from the Red River basin and South China Sea (Hoang et al., 2009; Wang et al., 2014a) indicate that the Jinsha River still provided sediment to the Red River before the late Miocene. Single grain K-feldspar Pb isotopes data suggest that the rivers in the Sichuan Basin and Songpan-Garze Block were disconnected from the Red River catchment prior to 24 Ma and 12 Ma, respectively (Clift et al., 2008). Therefore, we suggest that the Jinsha River was still connected to the Red River before the late Miocene. In contrast, based on similarity of detrital zircon U-Pb age distributions between the Yangtze gravel sediments near Nanjing (Guizishan, Lingyanshan and Xiaopanshan) and modern sands of the Yangtze at Wuhan and Nanjing, Zheng et al. (2013) suggest that the Yangtze River evolved close to its modern state before ~24 Ma. However, the similarity in detrital zircon age distributions between the Yangtze gravel sediments and modern sands is nice but insufficient evidence to prove that a river similar to the modern Yangtze already formed before ~24 Ma. We mix the modern detrital zircon U-Pb ages of the Gan, Han and Xiang rivers (Mix4 in Fig 5.10) to represent sediment from the middle-lower Yangtze before the formation of the Three Gorges. The mix of modern detrital zircon U-Pb ages of the Gan, Han, Xiang, Jialing and Min rivers (Mix5 in Fig 5.10) is utilized to represent the sediment to Nanjing sections when the Jinsha River was flowing into the Red River. Fig 5.10 shows that Mix5 has similar age distributions with LYS, XPS, GZS and Nanjing and plots close together with Nanjing, LYS, XPS and GZS in the MDS map, suggesting that the paleo-Yangtze (without the Jinsha River) already yielded similar zircon age distributions to those of the modern sample collected at Nanjing.

Because the Three Gorges formed before 22.9 Ma and the Jinsha River lost its connection to the Red River before the late Miocene, the Dadu river could only started to provide sediment to the middle-lower reaches after the late Miocene. Moreover, the young rocks in the Dadu River basin exhumed to the surface before 18.5 Myr ago. Consequently, young muscovite and biotite grains should have been observed in the Pliocene-Quaternary sediments (YC2-YC4, ZL4-ZL6, XG and YL-T) in the Jianghan Basin. We attribute the absence of young muscovite and biotite grains in these samples to a paleo-drainage pattern of the Dadu River flowing into the Jinsha River through the Anning River before the Quaternary (discussed in chapter 4). Sediment of the Dadu River was transported through the Anning and Jinsha rivers valley to the Mid-lower Yangtze. Young muscovite and biotite grains are not observed in Pliocene-Quaternary sediments (YC2-YC4, ZL4-ZL6, XG and YL-T) due to a longer-distance transport (~1800km versus ~1200 km) compared to its current course (Fig 5.9c). These muscovite grains have been abraded into undetectable grains by high velocity water flow in the Anning and Jinsha rivers when they arrived into mid-lower reaches or are a least diluted by other sediment sources. This is supported by fact that the Yalong River (see location in Fig 5.1c) muscovite grains almost cannot be detected in mainstream at Yichang in the middle reaches (Sun et al., 2016). Because the Yalong River joins the Anning River at 15km north of the Yalong-Jinsha confluence (Fig 5.1c), sediment from the Yalong River traveled similar distance to mid-lower Yangtze
compared with sediment from the Dadu River when it was flowing southward into the Anning River. The young muscovites from the Dadu River were observed in ZL2 (~1.2 Ma) in the Zhoulao Core (Fig 5.8). Combination of data from the Xingou and Zhoulao cores (discussed in chapter 4) and Yangtze gravel sediments suggest that the Dadu River was captured by river in the Sichuan Basin between 2.1-1.2 Ma.

Figure 5.10 A comparison of zircon data between modern samples from the Yangtze and Yangtze gravel sediments at Nanjing. a) Detrital zircon age distributions from Yangtze gravel sediments and potential source regions. Solid lines and gray shade are probability density plots and kernel density estimations. Mix4=Gan+Xiang+Han (in a ratio of 92 :93 : 95 ), Mix5=Gan+Xiang+Han+Jialing+Min (92 :93 : 95 : 98 : 96), b) Non-metric multi-dimensional scaling (MDS) plot of zircon data. Detrital zircon U-Pb data from Zheng et al. (2013).
5.3 The link between the formation of the Three Gorges, tectonism and climate change

The uplift of the eastern Tibetan Plateau to its current elevation was reached during the Eocene - middle Miocene (Hoke et al., 2014; Li et al., 2015). In contrast, the Sichuan Basin, as part of the Yangtze craton, is an old and intact block that experienced little internal deformation during the collision between India and Asia. Consequently, the elevation of the Sichuan Basin remained low when the eastern Tibetan Plateau rose. Therefore, the originally southward flowing rivers (before 36.5 Ma) in the Sichuan Basin were blocked due to the uplift of the southeastern Tibetan Plateau. At the same time, the uplift of the Tibetan Plateau caused the commencement of the Eastern Asia monsoon and aridification in the Asian interior. Several kilometers thick sequences of lacustrine and evaporate deposits in the Jianghan Basin between 56 - 36 Ma and Paleoclimate reconstruction based on these sediment deposits suggest a dry and hot paleoclimate (Wang et al., 2012a; Zhang et al., 2006; Zheng et al., 2013). The absence of evaporate deposits from about 36 Ma in the Jianghan Basin implies an increase of the precipitation in the middle-lower reaches of the Yangtze. Additionally, the occurrence of loess deposition in China since 29 - 22 Ma (Garzione et al., 2005; Guo et al., 2002) also suggests that the onset of the winter monsoon in northern China and summer monsoon in southern China started around that time. Therefore, the intensification of precipitation in the southern China is expected to increase river incision rate and accelerate the middle Yangtze River extension into the Sichuan Basin to form the Three Gorges.

The apatite and zircon (U-Th)/He data from elevation transects collected within river valleys of the upper Jinsha, Yalong and Dadu rivers show a rapid cooling between 15 - 10 Ma. (Clark et al., 2005; Ouimet et al., 2010; Tian et al., 2015), implying a significant acceleration of uplift of the southern Tibetan Plateau since 15 - 10 Ma. This intensification of surface uplift is also observed at southeastern plateau margin in the Longmen Shan range (Tian et al., 2013; Wang et al., 2012b). This rapid uplift event might have been the cause that the Red River disconnection from the Jinsha River before the late Miocene. Meanwhile, the intensification of the southeastern Asia Monsoon commenced at the late Miocene (11 - 8 Ma) (An et al., 2001; Sanyal et al., 2010), which may have accelerated the westward extension of the river in the Sichuan Basin and thus the capture of the south flowing Jinsha River.

6 Conclusions

In this study, we present new muscovite and biotite $^{40}$Ar/$^{39}$Ar ages and muscovite geochemistry data for the Yangtze gravel sediments in the mid-lower reaches of the river. The muscovite and biotite $^{40}$Ar/$^{39}$Ar ages of modern sediments from main stream are remarkably different from those of the Yangtze gravel sediments, which is caused by changes in drainage patterns and exhumation young rocks in the Dadu River basin after 18.5 Ma. The combination of muscovite and biotite $^{40}$Ar/$^{39}$Ar ages and muscovite geochemistry data suggests that the formation timing of the Three Gorges is at some time between 36.5 Ma and 22.9 Ma. The originally south flowing Jinsha River was captured by a river flowing into the Sichuan Basin before the late Miocene.
Appendix 5A

The references list of the published muscovite and biotite data of the Dabie-shan

Muscovite:

Eide, E.A., McWilliams, M.O., Liou, J.G., 1994. $^{40}$Ar/$^{39}$Ar geochronology and exhumation of high-pressure to ultrahigh-pressure metamorphic rocks in east-central China Geology 22, 601-604.


Liu, X.C., Jahn, B.-m., Dong, S.W., Lou, Y.X., Cui, J.J., 2008. High-pressure metamorphic rocks from Tongbaishan, central China: U-Pb and $^{40}$Ar/$^{39}$Ar age constraints on the provenance of protoliths and timing of metamorphism. Lithos 105, 301-318.


Webb, L.E., Hacker, B.R., Ratschbacher, L., McWilliams, M.O., Dong, S.W., 1999. Thermochronologic constraints on deformation and cooling history of high- and ultrahigh-pressure rocks in the Qinling-Dabie orogen, eastern China. Tectonics 18, 621-638.


Biotite:


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Webb, L.E., Hacker, B.R., Ratschbacher, L., McWilliams, M.O., Dong, S.W., 1999. Thermochronologic constraints on deformation and cooling history of high- and ultrahigh-pres-
sure rocks in the Qinling-Dabie orogen, eastern China. Tectonics 18, 621-638.

Chapter 6

$^{40}\text{Ar}/^{39}\text{Ar}$ mica dating of late Cenozoic sediments in the upper Yangtze: Implications for sediment provenance and drainage evolution

Xilin Sun, Chang’an Li, K.F. Kuiper, Zengjie Zhang, L. Gemignani, Vincent de Breij, J.R. Wijbrans

Based on: Sun, X.L., Li, C.A., Kuiper, K., Zhang, Z.J., L. Gemignani., Vincent de Breij., Wijbrans, J. “$^{40}\text{Ar}/^{39}\text{Ar}$ mica dating of the “Yangtze gravel” sediments in the mid-lower Yangtze reaches: implications for sediment provenance and development of the Yangtze River”. Prepared form for submission to Quaternary Research.

Abstract

The development of the river systems in East Asia is closely linked to the uplift of the Tibetan plateau caused by collision of the India-Eurasia continents. The Yangtze River is the largest river in Asia and the timing and exact causes of its formation are still a matter of debate. Here we use $^{40}\text{Ar}/^{39}\text{Ar}$ dating of detrital micas (muscovite and biotite) and muscovite geochemistry to constrain the evolution of the upper Yangtze River. The combined data suggest that the upper Jinsha River (the mainstream of the upper Yangtze drainage system) lost its connection with the southward flowing Red River upstream from Shigu town at least before the Pliocene. The Yalong River (a current tributary to the upper Yangtze) flowed east of Shigu through the Yuanmou Basin into the Red River, but abandoned this connection and turned east instead of south before ~4.8 Ma. Our results rule out the possibility that these capture events at Shigu and Yuanmou took place in Quaternary as suggested by others. The current flow of the Jinsha River between Shigu and Panzhihua is ~100 km north, ~170 km south followed by ~150 km east. We observe similar flow patterns before 1.58 Ma, suggesting that this flow direction of the Jinsha already formed >1.58 Ma. Our data also shed new light on the evolution of the Dadu River. The Dadu River and Jinsha river are not connected through the Anninghe Fault at least since 1.58 Ma. We propose that these capture events are closely linked to the tectonic processes in the eastern Tibetan Plateau and intensification of the East Asian monsoon resulting from the uplift of the eastern Tibetan Plateau.
1 Introduction

The uplift of the Tibetan Plateau caused changes in topography and climate and in turn changed the drainage patterns of rivers in the periphery of the Tibetan Plateau. The Salween and Mekong rivers originate from the eastern Tibetan Plateau and flow southwards into the South China Sea. In contrast, the Jinsha, Yalong and Dadu rivers, that also drain the eastern Tibetan Plateau, flow southward and then turn eastward to flow into the East China Sea (Fig 6.1a), as part of the Yangtze drainage system. Previous studies proposed that these rivers originally all flowed southward into the South China Sea and at some point in time were captured by the middle Yangtze (Barbour, 1936; Brookfield, 1998; Clift et al., 2008; Hoang et al., 2009; Kong et al., 2009; Kong et al., 2012; Yan et al., 2012). However, the cause(s) for these capture events remains controversial and no consensus exists on the exact timing of these capture events (Barbour, 1936; Clark et al., 2004; Clift et al., 2006a; Clift et al., 2008; Kong et al., 2009; Kong et al., 2012; Yan et al., 2012), with one school of thought proposing early formation of the Yangtze drainage system before the Miocene, and another advocating a late capture and formation of the current Yangtze as late as the Pliocene.

One way to approach this controversy is to unravel sedimentary provenance in river systems over time. Single proxies, for example, chemical, mineralogical or isotopic data, only provide limited constraints on the sedimentary provenance. Multiple chemical and isotopic proxies of single detrital minerals can extract more robust provenance information (Haines et al., 2004). In this study, we use $^{40}$Ar/$^{39}$Ar ages of micas (muscovite and biotite) and muscovite geochemistry from the eastern Tibetan Plateau to identify the provenance and evolution of the upper Yangtze River. Muscovite and biotite have limited resistance to physical abrasion and chemical weathering, and thus may reveal information about recent tectonic events in their source area due to their low closure temperatures (350 - 425 °C and 300 - 350 °C, respectively (Harrison et al., 2009; McDougall and Harrison, 1999)). Both muscovite and biotite are less likely to survive an orogenic cycle, when compared with for example zircon. Muscovite is the most common mica, found in the granites, pegmatite, gneisses and schists. Biotite is a major rock-forming mineral found in felsic-intermediate igneous rocks, and low to medium grade metamorphic rocks and are thus proxies for weathering of crystalline, middle crustal rocks exposed in the hinterlands. $^{40}$Ar/$^{39}$Ar ages of muscovite and biotite have been successfully exploited as provenance tool in many studies (Clift et al., 2004; Clift et al., 2006b; Haines et al., 2004; Hoang et al., 2010; Najman et al., 1997; Pierce et al., 2014; Reynolds et al., 2012). In this study, the combination of detrital muscovite and biotite data allows us to provide some new insights into the development of the upper Yangtze River (mainly Jinsha, Yalong and Dadu rivers).

2 Geological setting and samples

2.1 Geological setting

The upper Yangtze River drainage system is formed by the Jinsha, Yalong, Min and Jialing rivers with the source of the Jinsha River generally regarded as the “true” source of the Yangtze. The upper Yangtze drainage covers most of the Eastern Tibetan Plateau,
including from west to east the Qiangtang Block, Yidun Volcanic Arc and Songpan-Garze Block (Fig 6.2a). The Jinsha River is the main focus of this study and is topographically divided by Shigu Town and Panzhihua city into three segments (Fig 6.1b): the upper Jinsha from its origin till Shigu, the middle Jinsha from Shigu till Panzhihua and the lower Jinsha River downstream from Panzhihua until the western limit of the Sichun Basin.

**Figure 6.1** Map showing the study area in the Yangtze River. The white lines represent the current rivers and the arrows their flow direction. The red circles are sample locations in this study. The red stars are sample locations of samples from Chapters 3 and 4. The inset in d shows the stratigraphic position of the samples in the sedimentary sequences. The black arrows in the rose diagrams indicate paleocurrent direction. The pink line in c shows the catchment and therefore potential source area for sample YB. The red lines in b represent faults.
The India-Eurasia collision has caused the development of a series of major regional fault zones in the eastern Tibetan Plateau. The strike-slip Ailao Shan-Red River and Xianshuihe-Xiaojiang Fault zones are the two most important structures in this area (Fig 6.1b). The strike-slip Ailao Shan-Red River fault has a right-lateral displacement of ~40 km in total since late Oligocene-early Miocene times (Schoenbohm et al., 2006) of which 5-6 km occurred in the past 4 Ma (Wang et al., 1998). The left-lateral Xianshuihe-Xiaojiang fault system became active around 13-10 Ma and has a total recorded displacement of ~60-90 km (Wang et al., 1998; Zhang, 2013).

The Panzhuhua-Yuanmou region (Fig 6.1d) is located in the north of the Yunnan terrane, that is bounded by these two major fault zones with in the northeast the Xianshuihe-Xiaojiang fault zone and in the southwest the Ailao Shan-Red River fault zone. This area is characterized by widespread hundred-meter-thick lacustrine sediments (Xigeda Formation, \(^{26}\)Al and \(^{10}\)Be burial ages of 1.34-1.58 Ma, (Kong et al., 2009)). To the south of the Panzhuhua, more than 650 m well preserved late Neogene fluviolacustrine sediments...
are exposed in the Yuanmou Basin (Fig 6.1d). The depositional age of these sediments ranges from 4.9 to 1.4 Ma based on the paleomagnetic data (Zhu et al., 2008).

The Jianchuan Basin is located ~200km west of the Yuanmou Basin and ~30km south of the so-called “First Bend”: the Yangtze River flows southward through a deep mountain valley and makes an abrupt turn northward at Shigu Town (Fig 6.1b & c). The straight 1-4 km wide Yangbi Valley (Fig 6.1c), connects the Jianchuan Basin and the First Bend and is regarded as the paleo-course of the Jinsha River connection to the Red River (Clark et al., 2004). Clift et al. (2006a) and Clark et al. (2004) suggest that topography development caused by uplift and deformation of the eastern Tibetan plateau resulted in a drainage pattern re-organization in this region. There are several smaller faults developed near and in the Jianchuan Basin. The Jianchuan Fault runs through the basin, the Zhongdian fault borders the basin in the north and the Heqing fault in the west (Fig 6.1b). Cenozoic strata are well exposed in the western part of the Jianchuan Basin, including Yunlong and Guolang Formations (Paleocene), Baoxiangsi Formation (upper Eocene), Shuanghe Formation (Miocene), Sanying Formation (lower Pliocene) and Jianchuan Formation (upper Pliocene) (Fig 6.2d). The Sanying Formation is exposed in hill sides and is deposited unconformably on Paleozoic to early Cenozoic rocks (Wang et al., 1998). The early Cenozoic sediments are intruded by a series of sub-volcanic syenites and trachytes dated at 40-30 Ma (Wang et al., 2001).

2.2 Sample description

In total, seventeen samples were collected from the Jianchuan (6 samples), Panzhihua (5 samples) and the Yuanmou (6 samples) regions (Table 6.1, Fig.1). In the Jianchuan region (Fig 6.1c and appendix Fig A.1), a sand sample SG was taken from a Quaternary terrace 20m above the current river bed in the Jinsha River valley near Shigu (Figs 6.1c & 6.2b). A medium grained fluvial sand (YR) was collected from the modern Yangbi River (Fig 6.1c) and a fluvial sand sample (LT) was collected from a Pliocene terrace in Yangbi River valley ~270m above the river bed (Figs 6.1c & 6.2c). Three fluvial sand samples (DN, DZT and CSC) were sampled from the Jianchuan Basin itself. The sample CSC was collected from the same location as sample YN23 in Zheng et al. (2014)(Zheng et al., 2014). This sample belongs to the Pliocene Sanying Formation and is dated at 4.2±0.8 Ma based on cosmogenic nuclide burial age dating (Zheng et al., 2014) (Fig 6.2d). Sample DN also belongs to the Pliocene (Xiang et al., 2009; Zheng et al., 2014)(Fig 6.2d). Sample DZT was collected from the Jianchuan Fm in the northeast of the Jianchuan Basin. For the Jianchuna Fm a range of depositional ages is proposed from Eocene (Gourbet et al., 2017) to Pliocene (Xiang et al., 2007; BGMRYP, 1990).

In the Panzhihua-Yuanmou region, three sand samples (Pan1, Pan5 & Pan6) were collected from the lacustrine sediments (Xigeda Formation) in the Jinsha River valley near Panzhihua (Fig 6.1d and appendix Fig A.2). Two samples (Pan4 & Pan7) were collected from fluvial sediments underneath the Xigeda Formation (26Al/10Be burial ages: 1.34-1.58 Ma (Kong et al., 2009)). Samples Pan1, Pan4 and Pan5 are located upstream of the Yalong-Jinsha confluence and samples Pan6-Pan7 originate from downstream of the confluence. Four fluvial sand samples (YM1-YM4) were collected from ~650 meter Pliocene sediment in the Yuanmou basin (Fig 6.1d). Fluvial sand samples LCR and JS were sampled from the
modern Longchuan and lower Jinsha rivers (Fig 6.1d), respectively. The depositional ages of these samples were given in Table 6.1.

3 Analytical methods

Medium sized (200-500 µm) muscovite and biotite grains were separated from 17 samples using conventional heavy liquid and magnetic separation techniques. Samples were handpicked under a binocular microscope to remove grains with signs of visible weathering or inclusions. The muscovite fraction was randomly split into two aliquots for either chemical analysis or age determination. The muscovite grains from the first aliquot were embedded in epoxy resin, polished to expose an internal surface and carbon coated for electron microprobe analysis. The major element geochemistry of muscovite grains was determined by a JXA-8530F HyperProbe Electron Probe Microanalyzer at the Electron Microprobe Laboratory, Utrecht University, the Netherlands. Wavelength dispersive spectrometers were used with 20nA beam current and 15 kV accelerating voltage.

Table 6.1 Summary of sample information. Mineral indicates mineral types separated for analysis (Ms = muscovite; Bt = biotite).

<table>
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<th>Location</th>
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<th>Description</th>
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<th>Longitude</th>
<th>Altitude (m)</th>
<th>Depositional age (Ma)</th>
<th>Reference for depositional ages</th>
<th>Mineral</th>
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<td>Quaternary</td>
<td>Fan et al., 2006</td>
<td>Ms and Bt</td>
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Note: Modern sediments are sampled using methods as described in Sun et al. 2016. The depositional age of samples LT, DN, DZT and SG are based on the geological map (Yunnan Bureau of Geology and Mineral Resources, 1974); Fan et al.(2006) and Xiang et al. (2009)
The muscovite grains from the second aliquot were wrapped into 6mm Al-foil packages and placed into discs with a diameter of 18.8mm and depth of 3.3mm for irradiation. An in-house standard, Drachenfels sanidine (DRA; 25.52±0.08 Ma) was used to monitor the neutron flux variation (J). Samples and standards were irradiated for 18 hours in the CLICIT Facility in Oregon State University Radiation Center. After irradiation single muscovite grains were loaded into 2mm-diameter holes of a 185 hole copper disk. This disk was pre-baked overnight in a vacuum chamber at 250°C to reduce contaminant air followed by baking in a ultra high vacuum-chamber at 120°C connected to a purification line and mass spectrometer. Total fusion analyses of single muscovite grains were performed using a 25W Synrad CO$_2$ Laser Instrument. The released gas was first purified by a cold trap (-70°C) to trap volatiles and then further cleaned in an ultra-high vacuum gas purification line by exposure to SAES NP10 (Fe-V-Zr alloy) getters. The Ar isotopes were measured by a ThermoFisher Helix MC multi-collector noble gas mass spectrometer (Helix) or Hiden HAL 3F Series 1000 Pulse Ion Counting Triple Filter quadrupole mass spectrometer (AGES). The software ArArCALC2.5 (Koppers, 2002) was used for data reduction and age calculation.

In addition to chemical data and age constraints we also measured flow directions based on sedimentary structures. Knowledge of paleo flow directions also provides information on sediment provenance. Where possible we measured the orientation of a-axes (the trend of the longest axis) of cobbles to constrain the paleo-currents. Twenty cobbles per sample of samples YM1, YM2, Pan4 and Pan7 were measured in the field and plotted in the rose diagram to show the direction of the pebble imbrication that is opposite to the flow direction of the river (Fig 6.1d).

In order to visually inspect our data, we used a non-matrix multidimensional scaling (MDS) statistical technique to plot muscovite and biotite ages and Al/(Si+Mg+Fe) of muscovite. Because some samples have a low number of $^{40}$Ar/$^{39}$Ar or EMP data (such as YM3), these samples are excluded in the MDS maps. We compute a table of Kolmogorov-Smirnov dissimilarities for each of the muscovite and biotite $^{40}$Ar/$^{39}$Ar ages and muscovite Al/(Si+Mg+Fe) ratios. We then visually approximate these two-dimensional tables as two-dimensional configurations of points by Multidimensional Scaling (MDS; Vermeesch, 2013). These MDS configurations allow a graphical assessment of the salient similarities and differences between the samples for each of the three datasets. Our conclusions are based on the combination of the muscovite and biotite $^{40}$Ar/$^{39}$Ar ages, muscovite geochemistry data and MDS plots.

4 Results

4.1 Microprobe analysis

The microprobe analyses of 252 muscovite grains from 14 samples are shown in Figs 6.3, 6.7c & d. Samples DN, DZT and MY3 yield insufficient muscovites for microprobe analysis. The muscovite geochemistry for the upper Jinsha, and Yalong rivers is obtained from previous work (Sun et al., 2016). Because the upper Jinsha (upstream from Shigu) and Yangbi rivers (Fig 6.1c) are the potential source of the Pliocene fluvial samples CSC, DN, DZT and LT, we compared the muscovite geochemistry of grains from these samples.
with these two rivers (Fig 6.3a & b). Sample SG represents the muscovite geochemistry of the upper Jinsha River during the Quaternary and is also shown in this figure for comparison. Muscovite grains from sample CSC display bimodal chemical distributions and overlap partly with the upper Jinsha River field (upper Jinsha and SG), suggesting that some of the grains come from the upper Jinsha River or an unknown/unsampled location with similar geochemistry (Figs 6.3 & 6.7). The data points of sample LT fall into fields of the Yangbi and upper Jinsha rivers and SG (Fig 6.3a & b).

Most data points of early Pleistocene lacustrine and fluvial samples Pan1, Pan4 and Pan5 fall into the fields of the lower Jinsha (JS) and upper Jinsha River (Figs 6.3 & 6.7). The Longchuan and Yalong rivers also can be potential sources of some muscovite grains in these samples. The chemical compositions of muscovites from early Pleistocene fluvial samples Pan6 and Pan7 are similar to those of the Yalong River and different from those of the lower Jinsha (JS) and upper Jinsha rivers (Fig 6.3e and f). Some data points of sample Pan7 do not plot in a field corresponding to the chemistry of muscovite in potential source rivers (Figs 6.3 & 6.7), which implies that these muscovite grains do not originate from the upper Jinsha and Yalong rivers. The muscovite geochemistry of fluvial sample YM4 (~2.1 Ma) is generally identical to the Longchuan River (Fig 6.3g & h). Some of the muscovites from fluvial sample YM2 (~4.1 Ma) overlap with the lower Jinsha River (JS). The muscovite geochemistry of fluvial sample YM1 (~4.8 Ma) is significantly different from those of sample YM4, the Yalong and lower Jinsha (JS) rivers.

4.2 $^{40}$Ar/$^{39}$Ar dating of muscovite

In total, 507 muscovite $^{40}$Ar/$^{39}$Ar ages from 17 samples were dated in this study. The muscovite ages for the Yalong and Dadu rivers are obtained from Chapters 3 and 4. In the Jianchan region, Quaternary fluvial sample SG from the upper Jinsha River valley is dominated by an age population ranging from 220-260 Ma with a 235 Ma peak which overlaps with the “peak” of Pliocene fluvial sample DZT (Fig 6.4). Due to the low amount of muscovite in Pliocene sample DZT only 8 muscovite grains could be dated, yielding ages from 33 Ma to 788 Ma with one “peak” at ~230 Ma (n=2). Muscovite grains from the Pliocene fluvial samples CSC, DN and LT yield similar age distributions (Figs 6.4 & 6.7). Most of the muscovites from these samples are distributed between 180 Ma and 240 Ma, with major peaks at 213 Ma (CSC), 220 Ma (DN) and 205 Ma (LT). Modern sand sample YB from the Yangbi River is dominated by an age cluster of 100-180 Ma and significantly different from samples DZT, CSC, DN and LT (Fig 6.4).

In the Yuanmou region all muscovite grains from the samples YM4 (~2.1 Ma) and YM1 (~4.8 Ma) are distributed between 580 Ma and 800 Ma with major peaks at 760 Ma (YM1) and 740 Ma (YM4), respectively (Fig 6.5k and n). This age population overlaps well with 660-800 Ma population of the Longchuan River (LCR). Consequently, these two samples are plotted close together with the Longchuan River on the MDS map (Fig 6.7b). The age distributions of samples YM2 (~4.1 Ma) and YM3 (~3.1 Ma) are more complex and overlap with those of the lower Jinsha River (JS) (Fig 6.5j, l & m). In the Panzhihua region Pliocene samples Pan1 and Pan5 have similar age distributions and a large proportion of muscovite ages fall between 10-30 Ma and 200-240 Ma, suggesting that they
have similar source (Fig 6.5). Sample Pan4 yields ~93% of its muscovites in age range of 220-240 Ma and is similar to sample SG. Samples Pan6 and Pan7 are dominated by an age population of 120-160 Ma, accounting for 100% and ~52%, respectively, of the total dated grains. Another 45% of muscovite grains in sample Pan7 are distributed between 200-240 Ma and 600-900 Ma and overlap with the Yalong River.

Figure 6.3 Muscovite geochemistry of samples from the Jinchan (a, b) and Panzhihua (c-h) regions. The muscovite chemical compositions data of Jinsha (Shigu) are from Sun et al. (2016). Shaded areas represent muscovite geochemistry of the Yangbi, Yalong and Jinsha river and main tributaries. SG is a sample from a Quaternary sediment representing the muscovite geochemistry of the upper Jinsha River.
4.3 \(^{40}\text{Ar}/^{39}\text{Ar}\) dating of biotite

In total, 365 biotites from 14 samples were dated in this study (Figs 6.4 & 6.6), including 20 biotite ages from the Dadu river and 43 ages from the Yalong River (same sample as in chapters 3 and 4). Samples YM1-YM4 and LT yielded insufficient biotite grains for \(^{40}\text{Ar}/^{39}\text{Ar}\) dating. Twenty-nine detrital biotite grains from Quaternary sample SG showed a dominant population of 5-25 Ma (~62%) and a minor population of 80-92 Ma (~27%), which is significantly different from samples YB, DZT, CSC and DZ. All detrital biotite ages of the Pliocene samples DZT, CSC and DN are distributed between 20-40 Ma and similar to the Yangbi River (YB), implying that these biotite grains were derived from the catchment of sample YB (pink line in Fig 6.1c).

Figure 6.4 Muscovite and biotite \(^{40}\text{Ar}/^{39}\text{Ar}\) age distributions of samples from the Jianchan area. The black lines and shaded areas are respectively kernel density estimations (KDE) and probability density plots (PDP).
Most of the biotite grains from the Panzhihua region are younger than 100 Ma (Fig 6.6). The predominant age populations (0-20 Ma) of samples Pan1, Pan4 and Pan5 overlap well with that of sample SG. The peak of these age populations is slightly older than that of the Dadu River (Fig 6.6), implying these samples were not dominantly derived from this river. A dominant age population (70-95 Ma) of sample Pan5 partly overlaps with a minor age population of sample SG, suggesting that these muscovites come from the upper Jinsha River.

Figure 6.5 Muscovite $^{40}$Ar/$^{39}$Ar age distributions of sample from the Panzhihua-Yuanmou region. Black lines and shaded areas are kernel density estimation (KDE) and probability density plots (PDP). Muscovite ages of the Yalong River (YLJ) and Dadu River (DDH) are from Chapters 3 and 4, respectively. Note the difference in age scale (0-1000 Ma) in comparison with Figs. 6.4 and 6.6 (0-300 Ma).
5 Discussion

5.1 Provenance of sediments

In order to constrain the provenance of the Pliocene sediments collected in the upper Yangtze River drainage area, we compared the muscovite and biotite $^{40}$Ar/$^{39}$Ar ages and muscovite geochemistry with data obtained from modern sediments. Although the geochemistry and ages of the mica populations in these rivers, to some extent, could have changed since the Pliocene due to extension of river basin or capture events, we still could extract some useful information about the sediment provenance. The potential bias introduced by comparing modern day sediments with older sediments should be kept in mind when interpreting provenance.

5.1.1 Provenance of sediments from the Jianchuan region

The overlap in age population in samples DN, CSC and LT suggests that some of these muscovites were derived from a similar source area (Figs 6.4 & 6.7a). Although some muscovite geochemistry data fall in the fields of the Yangbi River (YB) (Fig 6.3a & b), the muscovite age distributions are markedly different from that of the modern Yangbi River (YB) that crosses the Jianchuan Basin. This means that almost all muscovites in these three samples did not originate from a river system similar to the Yangbi River of today. The major muscovite age populations (190-230 Ma) of these samples do not overlap with the major peak (230-250 Ma) but with minor peak (200-220 Ma) of the Quaternary Jinsha River (SG), suggesting that part of the muscovites are likely to be derived from the upper Jinsha River. This is consistent with the overlap in chemical compositions of muscovite grains between Pliocene samples (CSC and LT) in the Yangbi River catchment and upper Jinsha River (Fig 6.3a & b). The muscovite age peak (200-250 Ma) of sample DZT overlaps with the major peak of the Jinsha River, implying that these muscovite grains originated from upper Jinsha River.

The biotite age distributions of samples DN, CSC and DZT completely overlap with the Yangbi River (YB) but not with the upper Jinsha River (SG), which demonstrates that these biotite grains were derived from the Yangbi River and not from the upper Jinsha River. Moreover, the biotite $^{40}$Ar/$^{39}$Ar age of trachyte (36.7±0.6 Ma (Zhang and Xie, 1997)) in the Jianchuan Basin (Fig 6.2d) is in agreement with the major biotite age peak of samples DN, CSC and DZT. This demonstrates that these widespread trachytes (that contain almost no muscovite) in the Jianchuan Basin probably are the source of the biotite grains in samples DN, CSC and DZT.

Muscovite data suggest that none of the muscovites of samples DN, CSC and DZT were derived locally from the Yangbi River catchment and some grains were derived from the upper Jinsha River. In contrast, the biotite ages suggest that the biotites have a local origin. We suggest that the upper Eocene Baoxiangsi Formation in the Jianchuan Basin (Fig 6.2d) which originally was derived from the Jinsha River basin (Clark et al., 2004; Yan et al., 2012) is the potential source for these muscovites. Because the upper Jinsha River biotites can be diluted by high biotite concentration from trachyte in the Jianchuan Basin, they are maybe not detected in the 20-30 analyses per sample. Moreover, biotite is
Figure 6.6 Biotite $^{40}$Ar-$^{39}$Ar age distributions of samples from the Panzhihua region. Black lines and shaded areas are kernel density estimations (KDE) and probability density plots (PDP). Note the difference in age scale in comparison with Fig 6.5.

less resistant to the physical and chemical attack compared to muscovite and has shorter lifetime (Michał Kowalewski and J. Donald Rimstidt, 2003). We therefore infer that some of the biotite grains from the upper Jinsha River did not survive multiple physical and chemical weathering process in combination with their transport to the DN, CSC and DZT sample sites. This implies that there has been a connection and thus southward flow of the Jinsha river into the Yangbi River catchment, which deposited the Baoxiangsi Formation.
This is consistent with the observation that the upper Jinsha River flowed southward into the Red River before the Miocene (Clark et al., 2004; Clift et al., 2006a; Clift et al., 2008). All the foregoing suggests that the muscovite and biotite grains in these Pliocene samples were derived from the upper Eocene sediments (Baoxiangsi Formation) and trachytes in the Jianchuan Basin, respectively. The sediment provenance of samples LT, DN, CSC and DZT was summarized in Fig 6.8.

Figure 6.7 Non-metric multi-dimensional scaling (MDS) plots of muscovite \(^{40}\)Ar/\(^{39}\)Ar ages. Solid lines mark the closest neighbours and dash lines the second closest neighbours (based on Vermeesch, 2013). Because sample DZT only 8 muscovite ages, this sample is excluded from the MDS analysis to avoid significant bias.
No consensus exists on the age of the Jianchuan Fm from which sample DZT were collected. Gourbet et al. (2017) suggest that the Jianchuan Fm is 35.9 ± 1.1 Ma old based on two youngest detrital zircon U-Pb ages (2 of 17) from volcanoclastic. But all detrital biotite $^{40}$Ar/$^{39}$Ar ages (n=30) of fluvial sample DZT from the Jianchuan Fm fall in an age cluster of 37.5-32.3 Ma (section 4.2), corresponding well with the emplacement age (37-33 Ma) of the plutonic intrusions and volcanic rocks in the Jianchuan region (Gourbet et al., 2017 and references therein). This suggests that the Jianchuan Fm is younger than this ultrapotassic magmatic episode (37.5-32.3 Ma) in this region. Moreover, a Pliocene (2.4-3.1 Ma) age has been proposed for the Jianchuan Fm based on apatite fission track (AFT) ages (Xiang et al., 2009). In addition, the Jianchuan Fm is defined as the Pliocene in the regional geological map (BGMRYP, 1990). Based on the combination of our biotite data from DZT, apatite fission track (AFT) ages (Xiang et al., 2009) and regional geological map, we suggest the Jianchuan Fm belongs to the Pliocene.

5.1.2 Provenance of sediments in the Panzhihua region

The major age peaks in the populations of muscovite and biotite grains from early Pleistocene sediment (Pan1, Pan4 & Pan5) overlap with those of the Quaternary Jinsha River (SG) (Figs 6.5, 6.6 & 6.7), meaning that some of the sediments in these samples were derived from the upper Jinsha River (Fig 6.8). This corresponds with the results of the muscovite geochemistry data (Fig 6.3c & d) and implies a gateway between Shigu and Panzhihua during the early Pleistocene. Because only one muscovite grain in sample SG is younger than 100 Ma, the young muscovite grains (10-30 Ma) in Pan1, Pan4 and Pan5 are unlikely to originate from the upper Jinsha River (upstream of Shigu), but most likely come from the mainstream of the Jinsha River between Shigu and Panzhihua and/or unsampled small tributaries. Moreover, this young age peak is also narrower than the dominant age population (0-80 Ma) of the Dadu River (Fig 6.5), implying that these muscovites do not originate from the Dadu River. Therefore, we argue that the upper Jinsha River is the most important sediment contributor to Pan1, Pan4 & Pan5. The major muscovite (<80 Ma) and biotite age peak (4 Ma) of the Dadu River is not present in the samples Pan6 and Pan7 indicating that this river is probably also not the source of these two samples (Figs. 6.5 & 6.6). The dominant muscovite age population (120-165 Ma) in early Pleistocene samples Pan6 and Pan7 is not observed in the Jinsha and Yalong rivers (Fig 6.5), suggesting that muscovite grains between 120-165 Ma were not derived from these two rivers. Moreover, the absence of muscovite grains with ages between 120-165 Ma in Pan1, Pan4 and Pan5 demonstrates that muscovite grains in this age range in Pan6 and Pan7 were not derived from the mainstream and/or unsampled small tributaries between Panzhihua and Shigu. We suggest that part of sediments in Pan7 is derived from a local source. The muscovite grains with ages of 600-870 Ma (~28%) as seen in sample Pan7 closely matches with ages observed in the Yalong River, suggesting that these muscovite grains were supplied by the Yalong River. Therefore, sample Pan7 is likely to be a mix of sediments from the Yalong River and local source (Fig 6.8). This corresponds with the rose diagram that the paleocurrent direction is southwards (Fig 6.1d). The primary reason for absence of the Yalong and upper Jinsha rivers mica in lacustrine sample Pan6 is that large muscovite and
biotite grains (200-500 µm) from the Yalong and upper Jinsha rivers already sank before they were transported to the sampling site of this sample. Small grains might have reached Pan6 but we did not analyze grains <200 micron.

Although the muscovite age distribution of sample YM1 (~4.8 Ma) in the Yuanmou Basin is similar to that of the Longchuan River (sample LCR)(Fig 6.5), the muscovite geochemistry is different (Fig 6.3g & h). Moreover, the rose diagram of the cobbles of sample YM1 suggests that the provenance is located east of the sampling site (Fig 6.1d). Therefore, sediment in sample YM1 is likely to be derived from a small tributary of the Longchuan River originating from the Dongshan Mountains (see Fig 6.1d for location), which are characterized by Cretaceous and Paleogene sandstones (Fig 6.2e). Samples YM2 (~4.1 Ma) and YM3 (~3.1 Ma) generally overlap in muscovite age distribution with those of the Yalong and Jinsha (JS) rivers (Fig 6.5), which is consistent with the observation that ~47% muscovite grains of sample YM2 fall into the field of the Jinsha River (JS)(Fig 6.3g & h). We therefore suggest that muscovites in sample YM2 were derived from the Yalong River. Sample YM3 yields insufficient muscovites for geochemistry, similarity in age distribution between samples YM2 and YM3 implies that some of muscovites in sample YM3 were also derived from the Yalong River. The muscovite age distributions and geochemistry of sample YM4 (~2.1 Ma) are similar to the Longchuan River, demonstrating a derivation of sediment from the this river (Figs. 3 & 5). The dissimilarity in muscovite age between samples from the Yuanmou Basin and the Dadu River confirms that the latter is not the source of these sediments (Fig 6.5).

Available data in this study also support a scenario that samples YM2 and YM3 were derived from the Paleogene sediments in and near the Yuanmou Basin instead of the Yalong River like sample YM1. (Fig 6.2e). In that scenario the Yalong river could have been the source during the Paleogene for the sediments in the Yuanmou Basin. These sediments were then eroded, transported and deposited at the Pliocene site of samples YM1-YM4. This scenario could also lead to the similarity in muscovite age distributions and geochemistry between samples YM1–YM4 and the Yalong River (Figs 6.2e and 6.8). In addition, the rose diagram of cobble imbrication above sample YM2 shows that the paleocurrent direction is towards SE/SW where the Paleogene sediments are located (Fig 6.1d). Paleomagnetic data from the Pliocene sediments (YM1 – YM4 collected) suggest that the Yuanmou Basin rotated $-6.7^\circ\pm2.8^\circ$ (2.58 – 1.37 Ma) and $-1.9^\circ\pm2.8^\circ$ (4.29 – 2.58 Ma) counterclockwise and $5.3^\circ\pm3.0^\circ$ (4.91 – 4.29 Ma) clockwise (Zhu et al., 2008). Consequently, paleocurrent direction recorded by cobbles was not significantly disturbed by tectonic rotation and is reliable.

5.2 Implications for the development of the upper Yangtze River

The remarkable spatial and temporal variation in sediment provenance is largely controlled by reorganization of the drainage patterns. In the Jianchuan region, the biotites in the Pliocene sediments were not derived from the upper Jinsha River but from the trachyte in the Jianchuan Basin and demonstrate that the Jianchuan Basin losts its connection with the upper Jinsha River at least before the Pliocene (Fig 6.9b). Some muscovite grains in Pliocene samples DN, CSC and LT in the Jianchuan region were derived from the Eocene
Baoxiangsi Formation which originated from the upper Jinsha River (Clark et al., 2004; Yan et al., 2012), implying that the Jinsha River flowed southward through this area in the Eocene (Fig 6.9a). Moreover, burial ages of samples collected from caves on the walls of the Jinsha River valley at the First Bend suggest that the Jinsha River channel has incised below the wind gap near First Bend between 18 - 9 Ma (McPhillips et al., 2016) which is in agreement with the outcome of the present study. Additionally, apatite (U-Th-Sm)/He data from a vertical profile near the First Bend indicate a 30 - 20 Ma phase of river incision above the wind gap south of the First Bend (Shen et al., 2016). Therefore, combination of our data and data of McPhillips et al. (2016) and Shen et al. (2016) (McPhillips et al., 2016; Shen et al., 2016) suggests that the capture event at the First Bend occurred between 30 Ma and 18 Ma.

To the east of the Jianchan Basin, two models could be used to interpret the development of the Jinsha River based on the two scenarios of provenance analysis. In model I (Fig 6.9b), sample YM1 (~4.8 Ma) originated from one of the tributaries of the Longchuan River which originated from the Dongshan Mountains. Whether the Jinsha River flowed southward across the Yuanmou Basin into the Red River before 4.8 Ma

<table>
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<th>Sample</th>
<th>Age (Ma)</th>
<th>Direct supplier</th>
<th>Indirect supplier</th>
<th>Locality of source area</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSC</td>
<td>4.2</td>
<td>Sedimentary rocks and trachytes in the Jianchuan Basin</td>
<td>upper Jinsha</td>
<td></td>
</tr>
<tr>
<td>DN</td>
<td>Pliocene</td>
<td>Upper Jinsha and unsampled small tributaries</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DZT</td>
<td>~1.34</td>
<td>Local source</td>
<td></td>
<td>unclear</td>
</tr>
<tr>
<td>LT</td>
<td>1.36-2.73</td>
<td>Yalong and upper Jinsha rivers and local source</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pan1</td>
<td>1.34-1.89</td>
<td>Longchuan River</td>
<td></td>
<td>Yalong and upper Jinsha</td>
</tr>
<tr>
<td>Pan4</td>
<td>~2.1</td>
<td>Paleogene sediments in the Yuanmou Basin</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pan5</td>
<td>~3.1</td>
<td>Dongshanzhong Mountain</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pan6</td>
<td>~4.1</td>
<td>Dongshanzhong Mountain</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pan7</td>
<td>~1.34</td>
<td>Dongshanzhong Mountain</td>
<td></td>
<td></td>
</tr>
<tr>
<td>YM4</td>
<td>~1.34</td>
<td>Dongshanzhong Mountain</td>
<td></td>
<td></td>
</tr>
<tr>
<td>YM3</td>
<td>~1.34</td>
<td>Dongshanzhong Mountain</td>
<td></td>
<td></td>
</tr>
<tr>
<td>YM2</td>
<td>~1.34</td>
<td>Dongshanzhong Mountain</td>
<td></td>
<td></td>
</tr>
<tr>
<td>YM1</td>
<td>~1.34</td>
<td>Dongshanzhong Mountain</td>
<td></td>
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</tbody>
</table>

**Figure 6.8** Summary of sediment provenance of the sediments from the eastern Tibetan Plateau. Circles indicate sample locations. The solid black lines or dark gray areas indicate the direct sediment suppliers. The light gray black lines indicate indirect sediment supplier. The dash lines represents non-suppliers. LR: Longchuan River.
remains uncertain. Some of the sediments in samples YM2 and YM3 (~4.1-3.1 Ma) were derived from the Yalong River, implying that the Yalong River flowed southward across the Yuanmou Basin into the Red River during 4.1-3.1 Ma (Fig 6.9b). The combination of muscovite age and geochemistry data suggests that muscovite grains in sample YM4 (~2.1 Ma) were derived from the Longchuan River (currently flowing northwards). This indicates that the Longchuan River flowed northward and joined the Yangtze River at least before ~2.1 Ma. However, the lithostratigraphy and sedimentology in the Yuanmou Basin suggest that the Pliocene sediments deposited in lacustrine and fluvial environment (Urabe et al., 2001; Zhu et al., 2008), which precludes routing of a large river like the modern Jinsha River through the Yuanmou Basin during the Pliocene. Moreover, interpretation of sedimentation facies of these Pliocene sediments indicates a northward flowing river. We, therefore, rule out this model and argue that the southward flowing Yalong River was captured somewhere east of the Yuanmou Basin at least before the Pliocene.

In model II (Fig 6.9c & d), sample YM1 originated from the Dongshan Mountains and samples YM2-YM3 were derived from Paleogene sediments in the Yuanmou Basin, which originated from the southward flowing Yalong River across the Yuanmou Basin in the Paleogene (Fig 6.9c). Because model II is consistent with the lithostratigraphy, sedimentology and our flow directions of cobbles in the Yuanmou Basin, we suggest that the model II is more reliable compared to model I and the Yalong River lost its connection to the Red River before the Pliocene. This agrees with the findings of Clift et al. (2008) and Hoang et al. (2009) that the Red River lost its connection with the Jinsha River before the late Miocene. For model II, more muscovite age and geochemistry data of the Paleogene sediments are required to comprehensively consolidate this scenario in future.

Muscovite and biotite data reflect that the upper Jinsha River is an important sediment contributor to samples Pan1, Pan4 and Pan5 (1.34-1.58 Ma, (Kong et al., 2009)). This indicates that the drainage channel from the Shigu to Panzhihua already formed before 1.58 Ma. Derivation of the Pan7 sediment from the Yalong River implies that the Yalong River connected to the Jinsha River before 1.58 Ma (Fig 6.9e). In contrast, based on detrital U-Pb ages from the fluvial and lacustrine sediments (Xigeda Formation) in the Jinsha River valley near Panzhihua, Kong et al. (2009) suggest that the Yalong River still flowed southwestward from Panzhihua during 1.34-1.58 Ma. However, the differences between the detrital zircon age distributions of samples from the Jinsha River valley are subtle (Fig A.3a), it is difficult to identify their salient differences or similarities based on the human eyes. We use a standard statistical technique called multidimensional scaling (MDS) to interpret these detrital zircon data and identify similarities and differences between samples. These samples from the Pleistocene sediments in the Jinsha River valley are generally not similar to the Yalong River but to upper Jinsha River (Fig A.3b), which is consistent with our mica data. Our findings agree with the studies of Hoang et al. (2009) and Clift et al. (2008) that the Jinsha River lost its connection with the Red River at least before the late Miocene.

Several lines of evidence suggest that the Dadu River flowed southward into the Anning River (Clark et al., 2004), a current tributary to the Yalong River. The Pleistocene sediments in Panzhihua region were not derived from the Dadu River, suggesting that the upper Dadu River was captured by an east flowing river in the Sichuan Basin before the Pleistocene (Fig 6.9d and e). Moreover, the Dayi conglomerate (burial age of ~2 Ma) in the
west of the Sichuan Basin was derived from the Min and Qingyi rivers and not from the Dadu River (Kong et al., 2011; Li et al., 2007). Therefore, the upper Dadu River was not captured by an east flowing river in the Sichuan Basin before ~2 Ma but flowed southward into the Anning River (Fig. 6.9e).

**Figure 6.9** Two models for the evolution of the Yangtze River since the Eocene. Black lines - rivers; gray lines - faults; black arrows indicate flow direction. 1 - Heqing Basin; 2 - Erhai Basin; 3 - Chenghai Basin; 4 - Binchuan Basin; 5 - Jianchuan Basin; 6 - Yuanmou Basin; 7 - Sichuan Basin.
We attribute the foregoing reorganization of drainage patterns to tectonic processes related to the eastern Tibetan Plateau. The capture event at the First Bend (30 – 18 Ma) is coincident with the deformation along the Xuelong – Diancang Mountains caused by the left-lateral ductile shear activity during the Oligocene - Miocene (~32-22 Ma) (Searle et al., 2010) and most active motion of the Red fault zone during 27-17 Ma (Gilley et al., 2003; Leloup et al., 2001). This left-lateral ductile shearing and motion of the Red River fault accommodated the continental extrusion caused by the collision between India and Asia. The capture events in the Panzhuhua-Yuanmou region happened before the Pliocene which could correspond to a sharp uplift of the Tibetan Plateau from the late Miocene (Clark et al., 2005; Ouimet et al., 2010). We also noted that the pre-Miocene and late Miocene uplift of the Tibetan Plateau is consistent with the intensified East Asian monsoon and erosion rate (An et al., 2001; Sun and Wang, 2005), which may also accelerate the headwater retreat and drainage reorganization in the studied region.

6 Conclusion

Combination of muscovite and biotite ages and muscovite geochemistry provides new constraints on the evolution of the upper Yangtze River. Our new data suggest that the upper Jinsha River originally flowed southward across the Jianchuan Basin before the Miocene and was captured at Shigu at least before the Pliocene. East of the Jianchuan Basin, the Jinsha River flowed southward across the Yuanmou Basin into the Red River before the Pliocene and was captured to east and north of this basin before 4.8 Ma. Our study confirms that the drainage channel from the Shigu to Panzhihua already was formed before 1.58 Ma. Our results also provide an indication that the Dadu River was not connected to the Jinsha River through the Anning River before the late Pliocene. This study shows that detrital muscovite $^{40}\text{Ar}/^{39}\text{Ar}$ dating is a useful and powerful tool to identify provenance, but we also suspect that detrital muscovite in sediment could also survive several cycles of erosion and deposition.
Appendix:

Fig. A.1 Outcrops of samples collected from the Jianchuan region.
Fig. A.2 Outcrops of samples collected from the Panzhihua-Yuanmou region. The number in the brackets is elevation of sample location.
Fig. A.3 Reassessment of the detrital zircon data from Kong et al. (2009). a) detrital zircon U-Pb age distributions of fluvial or lacustrine samples from the Jinsha River valley. Sample sites are shown in c. b) Multidimensional scaling (MDS) plot of zircon ages. c) A digital elevation map showing sample locations.
Chapter 7

Synthesis

In the previous chapters of this thesis, I have tested the validity of the use of detrital muscovite and biotite as provenance tool to constrain sediment provenance. Then I presented a study of the provenance of sediments collected from the sedimentary basins along the current course of the Yangtze using single detrital muscovite, biotite and zircon grains. Based on the variation in sediment provenance in space and time, I tried to reconstruct the development of the Yangtze River.

7.1 An overview of previous studies

Although the development of the Yangtze River has been studied for almost one century (Clark et al., 2004; Clift et al., 2008; Willis et al., 1906), this topic is still strongly debated. Previous studies focused on sediment samples collected from the upper Yangtze, the Jianghan Basin, the Yangtze delta and the Red River basin (including the South China Sea) to constrain the formation of the Three Gorges and the capture events that caused the upper reaches of the Red River to drain into the Yangtze. The prevailing approach in these studies to address provenance is dating of single grains of detrital zircon using U-Pb. One school suggests that formation of the Three Gorges can be dated back to Eocene-Oligocene time (Richardson et al., 2010; Wang et al., 2014b; Zheng et al., 2013), but another advocates a late formation during the Pliocene-Quaternary (Chen et al., 2009; Fan et al., 2005; Jia et al., 2010; Shao et al., 2012; Wang et al., 2009; Xiang et al., 2007; Yang et al., 2006; Zhang et al., 2016). In addition, some studies suggest that the Jinsha River (the main stream of the upper Yangtze) lost its connection to the southward flowing Red River during Quaternary (Kong et al., 2009; Kong et al., 2012; Li et al., 2009), while others argue that this happened before the late Miocene (Hoang et al., 2009; McPhillips et al., 2016; Wang et al., 2014a) or even before the Miocene (Clark et al., 2004; Clift et al., 2006; Clift et al., 2008; Wissink et al.; Yan et al., 2012; Zhao et al., 2015). Consequently, no consensus exists on the formation time of the Three Gorges and the timing of the Red River capture event, both crucial events in the evolution of the Yangtze.

In this thesis, muscovite and biotite $^{40}$Ar/$^{39}$Ar dating, muscovite geochemistry and zircon U-Pb were used to constrain the evolution of the Yangtze River. It is the first attempt to use detrital muscovite and biotite $^{40}$Ar/$^{39}$Ar dating to reconstruct development of the Yangtze River. The aims of this thesis are: 1) test the validity of detrital muscovite and biotite $^{40}$Ar/$^{39}$Ar dating as powerful provenance tool to constrain sediment provenance; 2) assess the human impact on muscovite transport in the Yangtze River; 3) solve the dispute on the formation time of the Three Gorges, and 4) constrain the timing of the Red River capture events.
7.2 Feasibility of using muscovite and biotite $^{40}\text{Ar}/^{39}\text{Ar}$ dating to constrain the development of the Yangtze River

7.2a Testing the tool

In chapter 2, the viability of using $^{40}\text{Ar}/^{39}\text{Ar}$ ages of single detrital muscovite and biotite grains as powerful sediment provenance tools is tested. The three exhumation pulses, classically described within the Alps as Variscan (350 – 280 Ma), Pre – Alpine (150 – 50 Ma) and Alpine (50 – 0 Ma) are clearly recorded by our detrital muscovite and biotite grains of nineteen medium grained sands collected from the rivers draining the Eastern Alps north of the Periadriatic line. Comparison of detrital muscovite and biotite $^{40}\text{Ar}/^{39}\text{Ar}$ ages of these samples when compared with ages derived from their known source areas suggests that muscovite and biotite geochronology is a reliable and powerful provenance tool in orogenic settings. In the Tauern Window in Austria current tectonic activity and exhumation is known in detail (Fox et al., 2016; Kurz et al., 2008; Zimmermann et al., 1994). Muscovite and biotite $^{40}\text{Ar}/^{39}\text{Ar}$ ages of modern sediments in the Tauern catchment show a correlation between higher erosion rates due to tectonic activity in their catchment and presence in river sediments of biotite and muscovite grains from that catchment. Therefore, detrital mica geochronology of river sediments should also be able to shed light on tectonic processes and erosion from the upper Yangtze catchment which presents the main focus of this thesis.

7.2b Human impact

Pre-recent samples from sedimentary basins in the Yangtze catchment were compared with modern sands from the major tributaries of the Yangtze to constrain sediment provenance in chapters 4 - 6. However, human activities can remarkably change the erosion patterns and sediment transport in the river system (Hu et al., 2013; Wan et al., 2015). Suspended sediment in the Yangtze River records the recent human controlled erosion patterns, while bed load sediment transport will also be influenced but with a certain lag time. In chapter 3, the sediment contributions of various tributaries calculated from suspended sediment load data from gauging stations and medium grained (200-500µm) muscovite data are remarkably different. We suggest that muscovites recorded an “old” unaffected erosion pattern but suspended sediment load data a “young” erosion pattern controlled by human activity. We show that the transport of medium sized muscovite grains in the Yangtze River is not significantly affected by human activity because these minerals are transported as bed load and take a longer time (>1000 years) to travel from source to delta. Therefore, the muscovite age distributions of modern sediments of major tributaries of the Yangtze are not influence by human impact and can reliably be compared with pre-recent samples from sedimentary basins.

7.3 The evolution of the Yangtze River

7.3.a Formation of the Three Gorges

The Jianghan Basin is located east of the Three Gorges at the beginning of the lower reaches of the Yangtze and records the timing and evidence for gateway between
the middle and upper reaches of the Yangtze. Sediments collected from the Zhoulao and Xingou cores in the Jianghan Basin suggest that the upper Yangtze River provided sediments to this basin before 3.5 Ma, implying that the Three Gorges formed before that time (chapter 4). Unfortunately, the studied sediment cores in the Jianghan basin do not extend further back in time than 4 Ma, and thus only provide an important but younger age limit for this event. Therefore, I studied the late Oligocene to middle Miocene Yangtze gravel sediments near Nanjing to find evidence for an older connection between the upper and lower reaches of the Yangtze. The data suggest that the Qingyi River in upper Yangtze provided a minor but diagnostic component of sediment to lower Yangtze, which gives additional constraints on the incision of the Yangtze River in the Three Gorges area before 22.9 Ma (chapter 5). Because the characteristic Qingyi River muscovite age peak is not observed in major tributaries in the middle and lower reaches, we exclude the possibility of another source in the middle-lower reaches than the Qingyi River. In addition, an Eocene sample from the Pailoukou Formation at Yichang and hydrocarbon-bearing shale and evaporite deposits in the Jianghan Basin (56 – 36.5 Ma) suggest that the upper Yangtze River did not provide sediment to the middle Yangtze before 36.5 Ma (chapter 5). This means that the Three Gorges formed at least after 36.5 Ma. Therefore, the combination of samples from the Jianghan Basin and Nanjing suggests that the formation time of the Three Gorges is somewhere between 36.5-22.9 Ma (Fig 7.1a) in agreement with the model where the Three Gorges are formed during the late Eocene – early Miocene (Wang et al., 2014b; Zheng et al., 2013). The formation of this gateway during the Pliocene-Quaternary as proposed by several studies does not agree with our results (Chen et al., 2009; Fan et al., 2005; Jia et al., 2010; Wang et al., 2009; Xiang et al., 2007; Yang et al., 2006). Variation in sediment provenance detected in these studies might reflect the capture event where the south flowing upper Dadu River was captured by rivers in the Sichuan Basin rather than formation of the Three Gorges (chapter 4). In addition, the absence of upper Cenozoic strata in the south and southeast of the Sichuan Basin suggests that a significant proportion of the Mesozoic and Cenozoic stratigraphy has been eroded by south flowing rivers. At least 1.3 km of sediment must have been removed in the Sichuan Basin since ~40 Ma (Richardson et al., 2008). The Jialing and East Min rivers are the likely candidates for the erosion of these sediments, implying that the flowed southwest and were tributaries of the Red River (Clark et al., 2004; Clift et al., 2008).

7.3b Timing of the change in flow direction of the upper Yangtze from south to east

The formation of the upstream part of the Yangtze, more specifically the timing of change in flow direction of the main rivers from south towards the South China Sea to east towards the East China Sea has been studied using samples collected from the Jianchuan Basin near the “First Bend” and from the Yuanmu Basin in the upper Yangtze River (chapter 6). The sediments in the first basin store information on the connection between the upper Jinsha and the Red River, while the latter stores information on the Yalong – Red River connection. The data from the Jianchuan Basin show that the upper Jinsha River did not deliver sediment to the Red River via the Jianchuan Basin at least before the Pliocene. However, Eocene sediments (belonging to the Baoxiangsi Formation) in the Jianchuan Basin are derived from the Jinsha River (Clark et al., 2004; Yan et al., 2012), suggesting
a connection between the Jinsha and Red rivers in the Eocene. Moreover, burial ages of samples collected from caves on the walls of the Jinsha River valley at the “First Bend” suggest that the Jinsha River channel has incised below the wind gap near the “First Bend” between 18 - 9 Ma (McPhillips et al., 2016) which is in agreement with the outcome of the present study. Additionally, apatite (U-Th-Sm)/He data from a vertical profile near the “First Bend” indicate a 30 - 20 Ma phase of river incision above the wind gap south of the “First Bend” (Shen et al., 2016). Therefore, combination of our data and data of McPhillips et al. (2016) and Shen et al. (2016) suggests that the capture event at the “First Bend” occurred somewhere between 30 Ma and 18 Ma. This is not consistent with a Quaternary Red River capture event suggested by Kong et al. (2012). This conclusion is made based on similarity in detrital zircon age distributions between Quaternary sediments in the Red River basin and the upper Jinsha River. However, our muscovite and biotite data suggest that the upper Jinsha River lost its connection to the Red River before the Pliocene and that these Pliocene sediments were derived from the local sedimentary rocks which originally originated from the Jinsha River. Because zircon is more resistant to physical abrasion and weathering compared to mica and more likely to survive multi-cycles of erosion and deposition (Andersen, 2013; Campbell et al., 2005; Dickinson et al., 2009), we suggest that these zircon grains in the Quaternary sediments originate directly from local sedimentary rocks which originally were derived from the upper Jinsha River.

The Pliocene sediments from the Yuanmou Basin, ~200km east of the Jianchuan Basin, show that these sediments were derived from the Paleogene sediments surrounding this basin. These Paleogene sediments were eroded, transported and deposited at Pliocene sites. This suggests that the Yalong River abandoned its connection with the Red River through the area of the Yuanmou Basin and turned east instead of south at least before the Pliocene (Fig 7.1). Samples from the Jinsha River valley near Panzhihua, about 400 km downstream of the “First Bend”, indicate that the “Yangtze” drainage channel from the Shigu to Panzhihua already formed before 1.58 Ma. This is inconsistent with the findings of Kong et al. (2009) that before 1.58 Ma stream flow directions from Panzhihua were in westward direction instead of east. Kong et al. (2009) made this suggestion based on the detrital zircon U-Pb age distributions of samples from the Quaternary sediments in the Jinsha River Valley. However, the differences between the detrital zircon age distributions are subtle, it is difficult to identify their salient differences or similarities based on visual inspection. I analyzed these detrital zircon data using standard statistical technique called multidimensional scaling (MDS) and get similar results as compared with our mica data. Our findings match with the studies of Hoang et al. (2009) and Clift et al. (2008) that the Jinsha River lost its connection with the Red River at least before the Late Miocene.

I summarize the evolution of the Yangtze River as follows: The upper Jinsha and Yalong rivers flowed southward into the Red River before 36.5Ma through the Jianchuan and Yuanmou basins, respectively, and deposited a large amount of sediments in these two basins during the Paleogene (Fig 7.1a). The rivers (paleo Jialing and Min rivers) in the Sichuan Basin also flowed westward and turned south into the Red River before 36.5 Ma (Clark et al., 2004; Clift et al., 2008). The upward and outward growth of the Tibetan Plateau caused the rise of the eastern Tibetan Plateau and increase in precipitation in the
Figure 7.1 The evolution of the Yangtze River. XDM – Xuelongshan – Diancang Mountain, JB – Jianchuan Basin, YB – Yuanmou Basin.
mid-lower Yangtze. The intensification of precipitation in the southern China accelerated river incision at the Three Gorges to amalgamate rivers in the Sichuan Basin somewhere between 36.5 - 22.9 Ma. The upper Jinsha River lost connection to the Red River across the Jianchuan Basin and turned eastwards between 30 – 18 Ma. Because detrital zircon U-Pb data from the Red River basin and South China Sea (Hoang et al., 2009; Wang et al., 2014a) indicate that the Jinsha River still provided sediment to Red River before the Late Miocene, we infer that the Jinsha River flow southward into the Red River through the Yuanmou Basin before the Late Miocene after the “First Bend” formed (Fig 7.1b). The originally southward flowing Yalong River was captured by the Yangtze River before the Pliocene (Fig 7.1c). A river drainage pattern similar to the modern Yangtze River established at least before the Pliocene.

7.4 The link between evolution of the Yangtze and tectonism and climate change

The uplift of the eastern Tibetan Plateau to its current elevation was reached during the Eocene - middle Miocene (Hoke et al., 2014; Li et al., 2015). In contrast, the Sichuan Basin, as part of the Yangtze craton, is an old and intact block that experienced little internal deformation during the collision between India and Asia. Consequently, the elevation of the Sichuan Basin remained low when the eastern Tibetan Plateau rose. Therefore, the originally (before 36.5 Ma) southward flowing rivers in the Sichuan Basin were blocked due to the uplift of the southeastern Tibetan Plateau. At the same time, the uplift of the Tibetan Plateau caused the intensification of the eastern Asia monsoon. Sediments in the Jianghan Basin change upward from thick sequences of lacustrine and evaporate deposits (56 – 36.5 Ma) to lacustrine (Oligocene) and fluvial (Neogene) sediments (Zheng et al., 2013). This change might be due to increasing precipitation in the middle lower reaches of the Yangtze since the Late Eocene times. The occurrence of loess deposition in China since 29 - 22 Ma (Garzione et al., 2005; Guo et al., 2002) suggests the onset of the winter monsoon in northern China and the summer monsoon in southern China. Intensification of precipitation in the southern China is expected to increase river incision rate and accelerate the extension of the middle Yangtze River into the Sichuan Basin to form the Three Gorges.

The upper Jinsha River abandoned the river channel passing through the area of the Jianchuan Basin and turned to northeast to form the “First Bend” between 30 Ma and 18 Ma. This reorganization event might be associated with the deformation along the Xuelong – Diancang Mountains (XDM) (see Fig 7.1b) caused by the left-lateral ductile shear activity during the Oligocene - Miocene (~32- 22 Ma) (Searle et al., 2010). This left-lateral ductile shearing accommodated the continental extrusion caused by the collision between India and Asia. The Jinsha River (including the Yalong River) lost its connection with the Red River before the Late Miocene (Hoang et al., 2009; Wang et al., 2014a). The Yuanmou Basin region is geologically controlled by Xianshuihe-Xiaojing Fault system which became active around 13-10 Ma and has a total recorded displacement of ~60-90 km (Wang et al., 1998; Zhang, 2013). The movement of this fault system may have been the trigger of the Yalong River capture event.
7.5 Limitations

The Yangtze River yields a complex mixture of sediment due to the contribution of multiple sources and a great variety of bedrock in its large river catchment. The sediment in the mid-lower reaches of Yangtze records non-unique and spurious features that make it difficult to identify source areas. As a consequence, it is difficult to trace sediment provenance of all minor components using one single provenance tool. The combination of multiple provenance proxies can potentially extract more robust information about sediment provenance. Although I used in all cases at least two approaches of muscovite and biotite \(^{40}\text{Ar}/^{39}\text{Ar}\) dating, zircon U-Pb age, muscovite geochemistry in this thesis, some minor components of sediments in the Yangtze River basin still cannot be identified. For instance, sediment from the Jinsha River cannot be easily detected in the sediments from the lower reaches of Yangtze using various approaches in this study due to dilution and physical abrasion. Therefore, more provenance tools are needed to constrain more minor components. In addition, the number of analyzed muscovite and biotite grains per sample for geochronology and geochemistry is not enough to identify all minor fractions. We analyzed 50-60 muscovite or biotite grains per sample for most samples from the Yangtze gravel sediments or mainstream and 30-40 grains per sample for most of the major tributaries. About 20 muscovite grains per sample were analyzed by electron microprobe. Although 30 and 50 grains were analyzed, ensuring with 95% certainty that no fraction greater than resp. 15% and 11% was missed from the underlying detrital population (Vermeesch, 2004), increasing the number of analyzed grains will increase the likelihood of identifying more minor components.

In chapter 4, samples from two cores (Zhoulao and Xingou cores) are insufficient to provide a complete picture of sediment provenance in the Jianghan Basin in terms of lateral variation in sediment provenance over time since the Pliocene. Moreover, these two cores only cover late Cenozoic (~4 Ma) sediment in the Jianghan Basin. Samples from these two cores only prove that the Three Gorges formed at least before than 3.5 Ma. Although Miocene and Eocene samples from the Yangtze gravel sediments in mid-lower Yangtze were studied in chapter 5 to compensate for this limitation, more continuous records in the center of the Jianghan Basin can provide more precise information about the development of the Yangtze River. Therefore, the samples from longer and continuous cores will be very important for future studies.

7.6 Outlook

Because muscovite is considered as less resistant to chemical and physical attack when compared to zircon, it is therefore unlikely to survive multiple cycles of deposition and erosion. However, our data from the Jianchuan and Yuanmou basins imply that muscovite can survive at least two cycles of deposition and erosion if the depositional basin is not far from the source area. Muscovites in the Pliocene sediments in the Jianchuan and Yuanmou basins might be derived from the Paleogene sediments in these two basins which were originally derived from the Jinsha River. These Paleocene - Eocene sediments are located south of the current Jinsha River and may be derived from the upper Jinsha and Yalong rivers. A provenance study of these Paleogene - Eocene sediments could provide
more constraints on the development of the Jinsha River.

Muscovite and biotite are relatively easily removed from the sediment by physical abrasion and chemical weathering by producing dioctahedral clay mineral such as kaolinite. (Fordham, 1990; Singh and Gilkes, 1991). It is not clear how muscovite and biotite grain size decrease with transport. The Yangtze river (6300 km) is a good natural analogue for studying variation in muscovite and biotite grain size from source to delta. Based on muscovite and biotite age distributions of major tributaries and mainstream, the sources of young muscovite (<60 Ma) and biotite (<5 Ma) grains in the Yangtze delta were confined to sediments originating in the Gonggashan and Danba regions in the Dadu River. Therefore, changes in muscovite and biotite grain size from the Gonggashan and Danba regions to delta can be constrained.
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Acknowledgements

After more than four years work, my PhD project is going to be finished. Without many people’s help and encouragement, my PhD thesis would never have come into being. I would like to take this chance to express my thanks to them.

The most important people who help me to finish my PhD project are my supervisors: Jan, Klaudia and Prof. Chang’an Li. Jan went to Wuhan, one of the hottest cities in China, to discuss my PhD project in the summer of 2012. Without your help, I would not have studied in Amsterdam. You picked me up at Schiphol airport and sent me to Uilenstede for my first visit to Amsterdam. You also help me a lot to get used to life in Amsterdam in the first year. Jan, thank you for your time and patience in supervising me over the five years. Sincere thanks go to Klaudia. I feel very lucky to choose you as my daily supervisor. You answered my questions about writing and experiment with infinite patience. You gave me many great suggestions on publication and PhD thesis. I learned a lot about $^{40}$Ar/$^{39}$Ar dating from you. Your excellent supervising and encourage kept me moving forward. My Chinese supervisor, Prof. Chang’an Li is the one who enlightened me first in my research career. You set up my master project and then initiated the Yangtze project with Jan to be my PhD project. Later, you also provided financial support for my sampling work and residential allowance in Amsterdam.

I would like to express my warm thanks to Roel. I started doing mineral separation in the first week once arriving at Amsterdam. You were always kindly offering help to me. Beyond that, you always had better solutions for my problems, even those out of the mineral separation lab.

Many thanks to Fraukje for your help during my first year study. You supervised me a lot during my major courses study process at Vrije Universiteit Amsterdam. Casimir Nooritgedacht, Blas Caicoya, Maxime and Nick Huijzendveld gave me a lot of help and encouragement and brought more fun in my Amsterdam life. Thanks a lot.

I would like to thank Lorenzo for the enlightening discussion we have had about my PhD project in the past four years. You helped me collect samples from Yunnan Province, southwest China. We also had many unforgettable memories together during fieldwork in the Alps.

I would like to thank my colleagues in the Argon lab: John, Christel, Bertram, Lara, Marilyn, Lars, Antonio. John gave me many suggestions on my scientific writing and also problems that I encountered in my daily life in Amsterdam. Christel, Bertram and Marylin taught me how to use AGES, Helix and ArArcal. Lara, Lars and Antonio gave me big support during the experiment.
Many thanks to my colleagues in the Geology and Geochemistry Cluster at Vrije Universiteit Amsterdam: Alice, Janne, Ina, Jurrien, Onno, Mélissa, Clément, Igor, Yue Zhao, Monica, Michael, Stefanie. I had a wonderful time during lunch with you. I would like to express my thanks to Fenny and Barbara. Your help and assistant made my study and life easier in Amsterdam.

I also would like to take this opportunity to thank reading committee for devoting significant amount of time to this thesis: Prof. R.T. (Ronald) van Balen, Dr. C.J. (Kay) Beets, Prof. Huaning Qiu, Prof. Gert Jan Weltje and Prof. Sean Willett.

My Chinese colleagues in CUG: Wang Jietao, Zhang Zengjie, Zhao Juxing, Chang Guorui, Zhang Dai helped me to collect samples in China and delivered them to the Netherlands. Many thanks to all of you.

I also would like to acknowledge my Chinese friends in Amsterdam: Zhang Jun, Li Huan, Lin Bochao, Yu Meichen, Ma Yuan, Yu Liang, Wu Junhui, Zhou Xiaolong, Li Siqiao, Gu Yuan, Sun Yajie, Gao Wen, Peng Fei, Lin Yanhao, Yang Jilong, Zhang Lulu, Li Yue, Xu Pengqi, Sun Guanyi, Li Lintao, Qin Yang, OuYang Xiyu. My life in the Netherlands was more colorful because of you.

I also want to thank some friends who have left Amsterdam: Spring (春姐), Zuo Juan, Qiaoli, Jin Xia(霞姐), He Erkai, Qiu Hao, Wu Suwei. We had unforgettable and happy dinner.

Grateful words to my parents and older brother by the end, all my achievements also belongs to you all. 要特别感谢我的父母和哥哥的支持,没有你们的支持,我也不可能到荷兰学习完成我的博士论文。