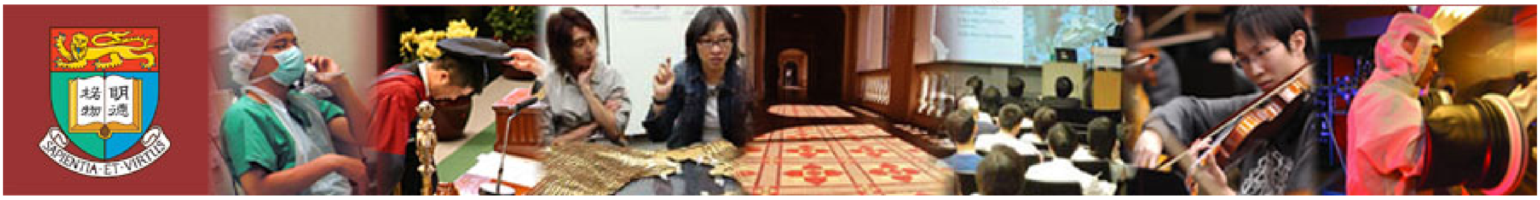

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Constraints on Cenozoic regional drainage evolution of SW China from the provenance of the Jianchuan Basin

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[1] Detrital zircon U-Pb geochronology was applied to Cenozoic fluvial sedimentary rocks from the Jianchuan Basin, Yunnan Province, China to constrain the provenance and the nature of paleo-drainage. Local geology testifies to a large river flowing through the Jianchuan Basin during the Paleogene and this previously has been linked to a paleo drainage system that connected the Qiangtang and Lhasa blocks to the South China Sea. The detrital zircon results from this study do not fit with this model and instead show provenance consistent with a river draining a watershed within the Songpan-Garze Complex, most likely from the northeast. From the late Oligocene and thereafter zircon provenance records greater contributions from erosion of local sources that surround the basin including the South China Block and Yidun Arc rocks that suggest loss of the northern sources. The timing for these changes overlap with regional deformation related to strike-slip faulting or displacement by shear strain rather than the later uplift associated with an expanding margin of the Tibetan Plateau.

Components: 5200 words, 6 figures.

Keywords: Jianchuan Basin; Red River; river capture; zircon U-Pb.

Index Terms: 8175 Tectonophysics: Tectonics and landscape evolution.

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1. Introduction

[2] The current pattern of the river systems that run through SW China, northern Vietnam and Myanmar are generally considered to be the result of Cenozoic tectonics associated with the India-Asia collision [e.g., *Brookfield*, 1998]. Some have argued that topographic expansion of the eastern margin of Tibet [*Clark et al.*, 2004] set the pattern of regional drainage, while others have suggested that deformation through uplift on strike-slip faults [*Lacassin et al.*, 1998] or displacement by shear strain [*Hallet and Molnar*, 2001] were the more important tectonic mechanisms that re-organized regional drainage. Central to resolving this debate is a better understanding of the nature of the paleo-drainage system that perhaps began as a single large paleo-River system that connected drainage of Tibet to the South China Sea [e.g., *Clark et al.*, 2004]. In this model a succession of river diversions and capture events driven by Cenozoic tectonics progressively reduced the drainage area of a single large (Mississippi scale) river system [e.g., *Brookfield*, 1998; *Clark et al.*, 2004].

[3] Support for a large single drainage system originated from interpretations of the regional landscape geomorphology that point to ancient reversal of the Middle Yangtze River and capture of the Upper Yangtze River and possibly the Upper Mekong, Upper Salween and Yarlung-Tsangpo rivers from a larger paleo-river system that drained into the South China Sea broadly along the current course of the Red River (Figure 1) which is why some refer to this system as the paleo Red River. Whether such a large drainage existed has yet to be proven and it can be argued that the Upper Mekong, Upper Salween and Yarlung-Tsangpo rivers were never part of such a large paleo-River system [*Clift et al.*, 2006; *Seward and Burg*, 2008]. To learn more about the regional paleo-drainage and the magnitude and timing of any changes we examined the provenance of detrital zircons from fluvial sedimentary rocks collected from the Jianchuan Basin, Yunnan Province, southwest China (Figure 2). Detrital zircon U-Pb geochronology has been widely used in provenance studies across western China [e.g., *Brugier et al.*, 1997; *Enkelmann et al.*, 2007; *Kong et al.*, 2009; *Weislogel et al.*, 2006], and on paleo-Red River sedimentary rocks from Vietnam [*Hoang et al.*, 2009].

[4] In many respects the fluvial sedimentary rocks within the Jianchuan Basin, located on the southern edge of the Triassic Yidun Arc, Songpan-Garze complex and Yangtze Craton, hold the key to establishing the existence and form of any large paleo drainage system. If the paleo river that once flowed through the Jianchuan Basin were part of a larger drainage system, that connected the Upper Yangtze watershed with the South China Sea, as proposed by *Clark et al.* [2004, 2006], then the sediment provenance for a larger river system should contain sources from the Songpan-Garze Complex and Yidun Arc. As this is an active tectonic region it is possible that there may have been some modification to the source rocks due to depths of erosion through the Cenozoic but apatite fission track and K-feldspar studies of bedrock from across the high elevation, low relief areas of the Yidun Arc record <2 km of denudation since the early Paleogene [*Reid et al.*, 2005]. The only deep exhumation is to be found on the eastern margins of Tibet where there is significant relief but these are localized features that have not led to widespread dissection of an ancient pre-uplift relict landscape [*Clark et al.*, 2005] hence at the regional scale the present-day outcrop distribution is not significantly different from that which existed in the Paleogene. The present-day Upper Yangtze catchment includes a large segment that flows along the Jingshajing Suture Zone (Figure 2), which has a band of Palaeozoic and Triassic sedimentary sequences up to 50–75 km wide as well as Triassic, Jurassic and a few Cretaceous granites in the tributary regions. Detection of these source ages in Jianchuan sedimentary rocks, especially zircon ages younger than 200 Ma [*Reid et al.*, 2007] would confirm a previous connection to an Upper Yangtze watershed. By contrast Middle Yangtze catchments (including the Dadu and Yalong Rivers) mainly fall within the Songpan-Garze Complex and to a lesser extent the South China Craton as it flows to the east. If the sedimentary rocks in the Jianchuan Basin were never part of a large paleo drainage system their provenance would unlikely change throughout the Cenozoic and be confined to local sources, mainly rocks of the Yangtze Craton, part of the South China Block.

2. Jianchuan Basin and Geological Setting

[5] Deformation associated with the India-Asia collision affected SW China in different ways at different times as collision progressed. Initially, with the northward motion of India relative to Eurasia stress was accommodated within the brittle upper crust, by clockwise rotation of blocks

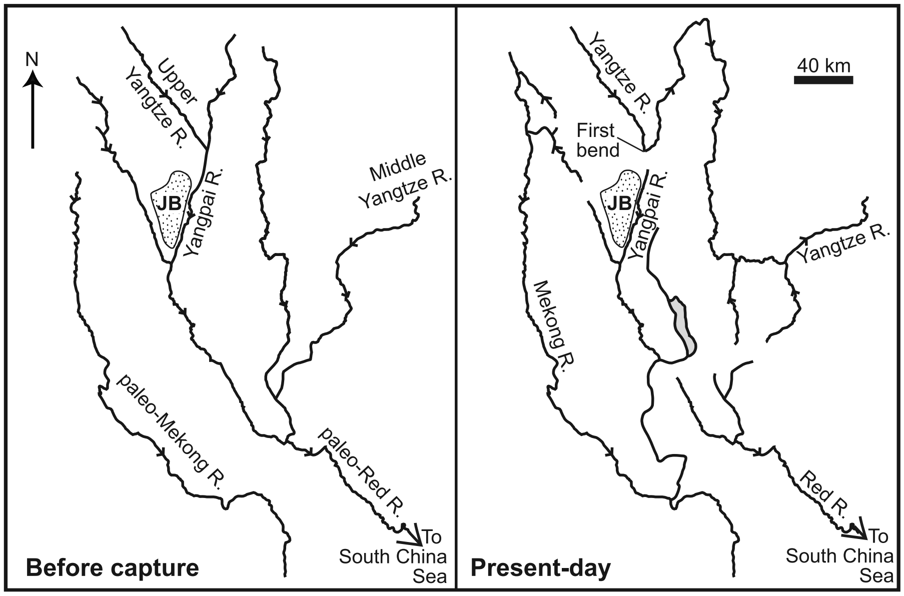

Figure 1. Summary of the river capture model showing how pre capture there was a connection between the rivers flowing through the Jianchuan Basin and the Upper Yangtze River [from *Clark et al.*, 2004].

bounded by left-lateral faults that form small circles about the eastern Himalayan syntaxis. Southeast extrusion of the Red River fault between 35 and 17 Ma [*Gilley et al.*, 2003] reflected the considerable regional stresses over that period. The nature of deformation then appears to have changed with onset of significant regional surface uplift in the Middle Miocene. Uplift in northern Vietnam and Yunnan Province in SW China has been recorded by the geomorphology of local rivers that cut deeply into a pre-uplift low relief landscape [*Schoenbohm et al.*, 2004]. It is possible that this most recent period of deformation was responsible for some drainage re-organization although changes associated with the strike-slip faulting could also explain earlier river capture events.

[6] The Jianchuan Basin lies at the junction between the Yangtze Craton (South China Block) and the Qiangtang Terrane (Figure 2) with the main basin depocenter currently located 40 km south of the modern Yangtze River. The basin is structurally and lithologically complex with limited age control. Sediments range from Paleocene to the Quaternary and are intruded by a series of sub-volcanic syenites and trachytes, that are in some locations as old as 42–24 Ma [*Wang et al.*, 2001] and younger where in places they intrude sediments mapped as Pliocene [*Yunnan Bureau of Geology and Mineral Resources*, 1990]. Paleogene sedimentation includes lacustrine siltstones, mudstones and sandstones of the Yunlong and Guolang Formations, (Figure 3) [*Yunnan Bureau of Geology and Mineral Resources*, 1990; *Xiang et al.*, 2007; *Zhang et al.*, 2010], and massive well-sorted fluvial sandstones of the Baoxiangsi Formation which show cross sets and scours as well as large channels and lag conglomerates [*Yunnan Bureau of Geology and Mineral Resources*, 1990; *Xiang et al.*, 2009; *Clark et al.*, 2004]. Based on reconnaissance study of Jianchuan Basin sedimentary rocks *Clark et al.* [2004] proposed that the paleoriver system that drained the Upper Yangtze valley was represented by only the Baoxiangshi Formation, which contained a lithostratigraphy appropriate for a large, fluvial system. Lithologic units above and below this unit were considered incompatible with a large, throughgoing fluvial system, although the overlying Jinsichang Formation also has a thick accumulation of conglomerates and sandstones intercalated with mudstone and marl, estimated at >3 km. The Miocene Shuanghe Formation lies unconformably on the Paleogene section and is dominated by much finer grained lacustrine sediments with coals. Pliocene sedimentation is confined to localized alluvial fans and volcanic tuffs (Figure 3b).

3. Methodology

[7] Overall, the stratigraphy of the Jianchuan Basin indicates a transition from a throughgoing fluvial system in the Paleogene to sedimentation associated with a more localized drainage system in the Neogene. As correlation across the basin is difficult

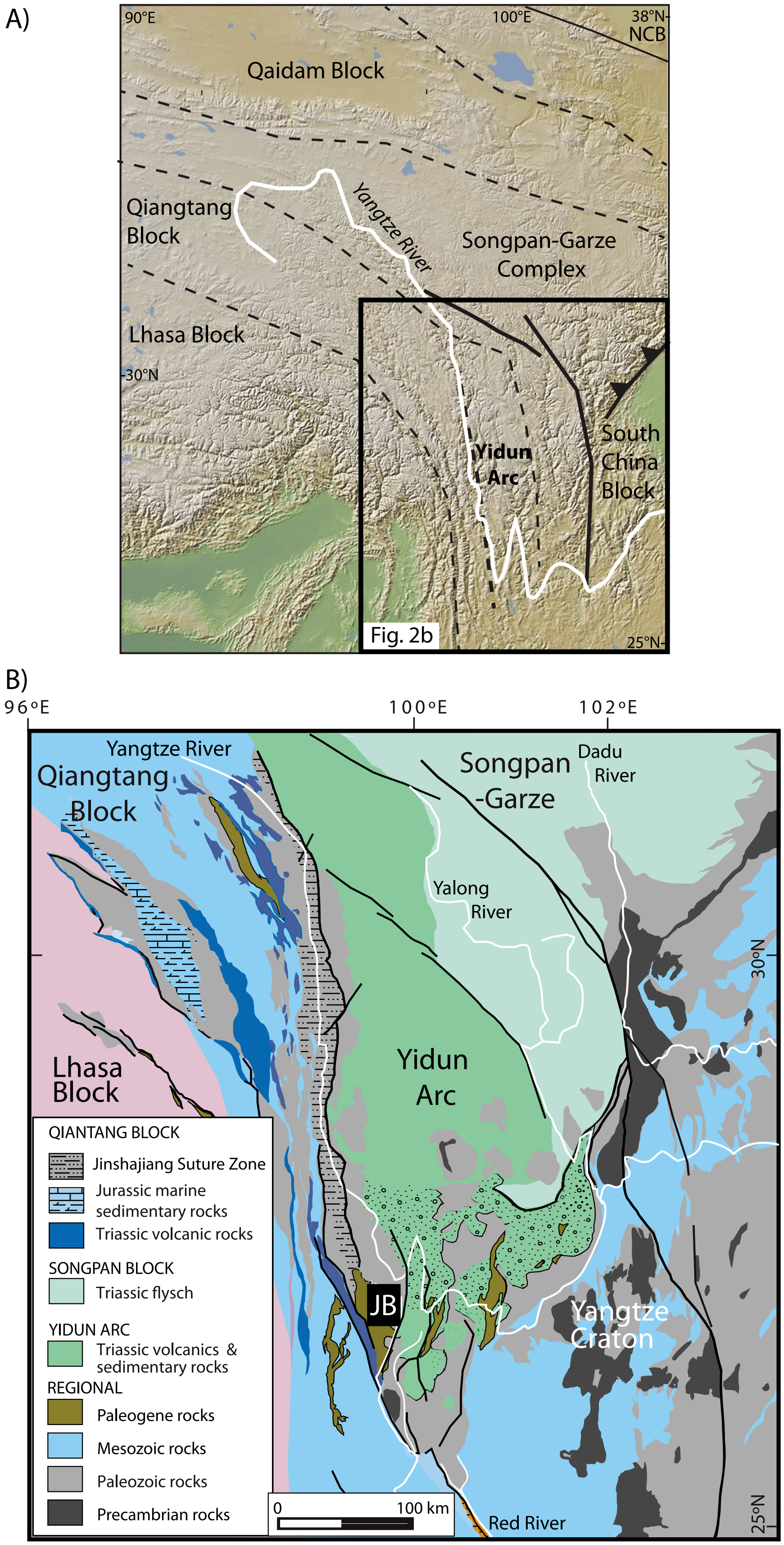
A)
90°E
100°E
38°N
NCB
Qaidam Block
Qiangtang Block
Yangtze River
Songpan-Garze Complex
Lhasa Block
30°N
Yidun Arc
South China Block
Fig. 2b
25°N
B)
96°E
100°E
102°E
Yangtze River
Qiangtang Block
Songpan -Garze
Dadu River
Yalong River
30°N
Lhasa Block
Yidun Arc
QIANTANG BLOCK
Jinshajiang Suture Zone
Jurassic marine sedimentary rocks
Triassic volcanic rocks
SONGPAN BLOCK
Triassic flysch
YIDUN ARC
Triassic volcanics & sedimentary rocks
REGIONAL
Paleogene rocks
Mesozoic rocks
Paleozoic rocks
Precambrian rocks
JB
Yangtze Craton
0
100 km
Red River
25°N

Figure 2

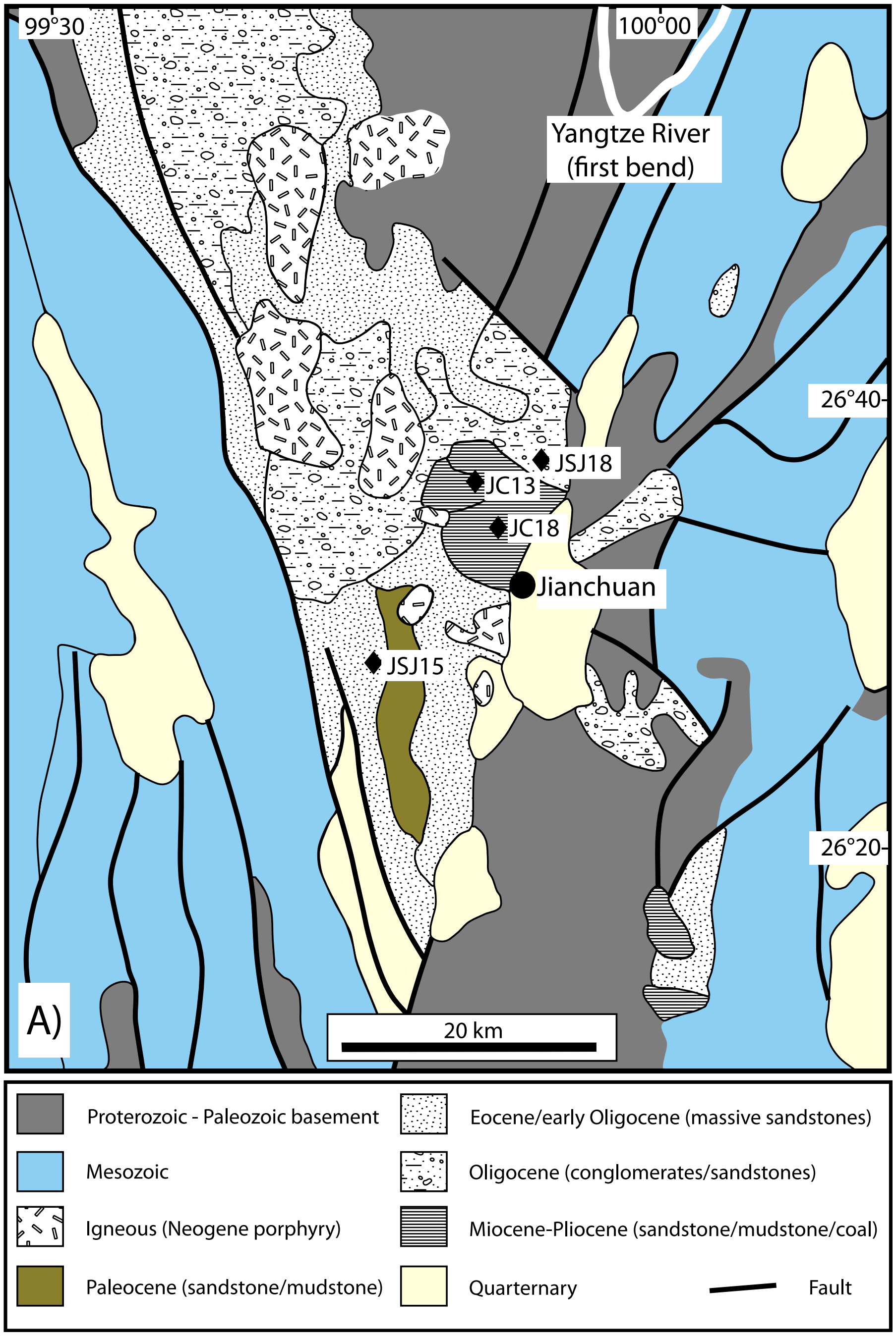

Figure 3. (a) Regional geology of the Jianchuan Basin showing location of samples used in this study. (b) Basin stratigraphy [*Yunnan Bureau of Geology and Mineral Resources*, 1990; *Xiang et al.*, 2009].

due to the widespread faulting samples were collected from sites described in geological survey reports. Typical of continental sedimentary rocks age control is rudimentary as distinctive index fossils are rare. *Yunnan Bureau of Geology and Mineral Resources* [1990] assigns an Upper Eocene and Oligocene age for the Baoxiangsi and Jinsichang Formations respectively on the basis of Paleogene

Figure 2. (a) Regional geology showing the relationship between the modern Yangtze River and tectonic blocks that form sediment sources in East Asia. (b) More detailed geological map showing the relationship of the studied basin to local geology.

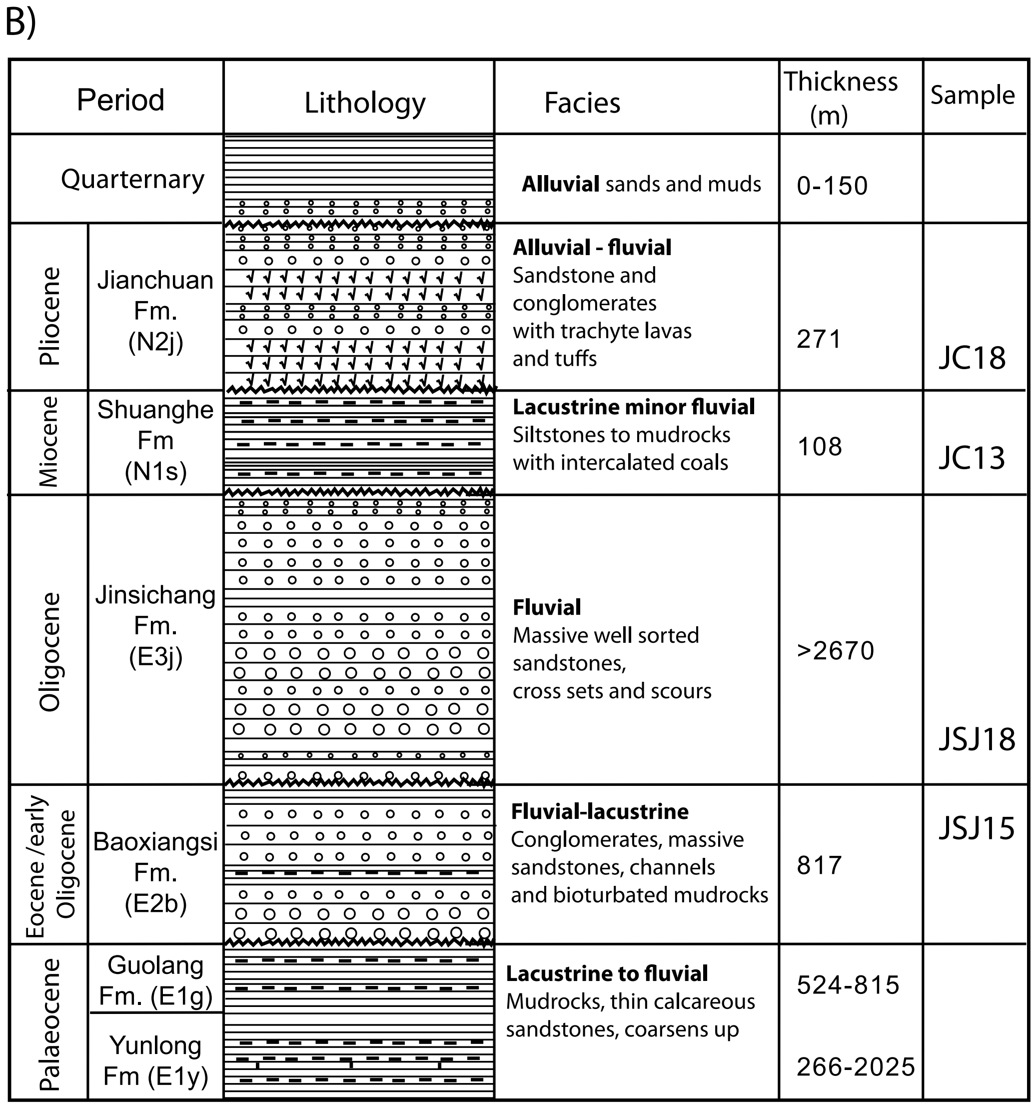

Figure 3. (continued)

assemblages of Charophytes and Ostracoda. Field evidence supports a Paleogene age as the fluvial units were deposited unconformably on fossil-bearing Paleocene calcareous mudstones and shales and are capped by Miocene rocks, seen on Chinese geological maps south of Jianchuan by a fossil-bearing, interbedded siltstone and coal sequence. Samples collected from the Miocene Shuanghe Formation and Lower Pliocene Jianchuan Formation contains dated volcanic tuffs and lacustrine deposits with coals.

[8] Determination of sediment provenance was based on detrital zircon geochronology. U-Pb ages were measured using a New Wave Nd:YAG 213 nm laser ablation system, coupled to an Agilent 7500a quadrupole ICP-MS based within the London Geochronology Research Group facilities at University College London. Real time data were processed using GLITTER laser ablation data reduction software version 4 (Macquarie University). Repeated measurements of external zircon standard Plesovice (TIMS reference age 337.13 ± 0.37 Ma) [*Sláma et al.*, 2008] and NIST 612 silicate glass [*Pearce et al.*, 1997] were used to correct for instrumental mass bias and depth-dependent inter-element fractionation of Pb, Th and U. Ages and probability density functions (Figure 4) were calculated using Isoplot [*Ludwig*, 2003]. Data and

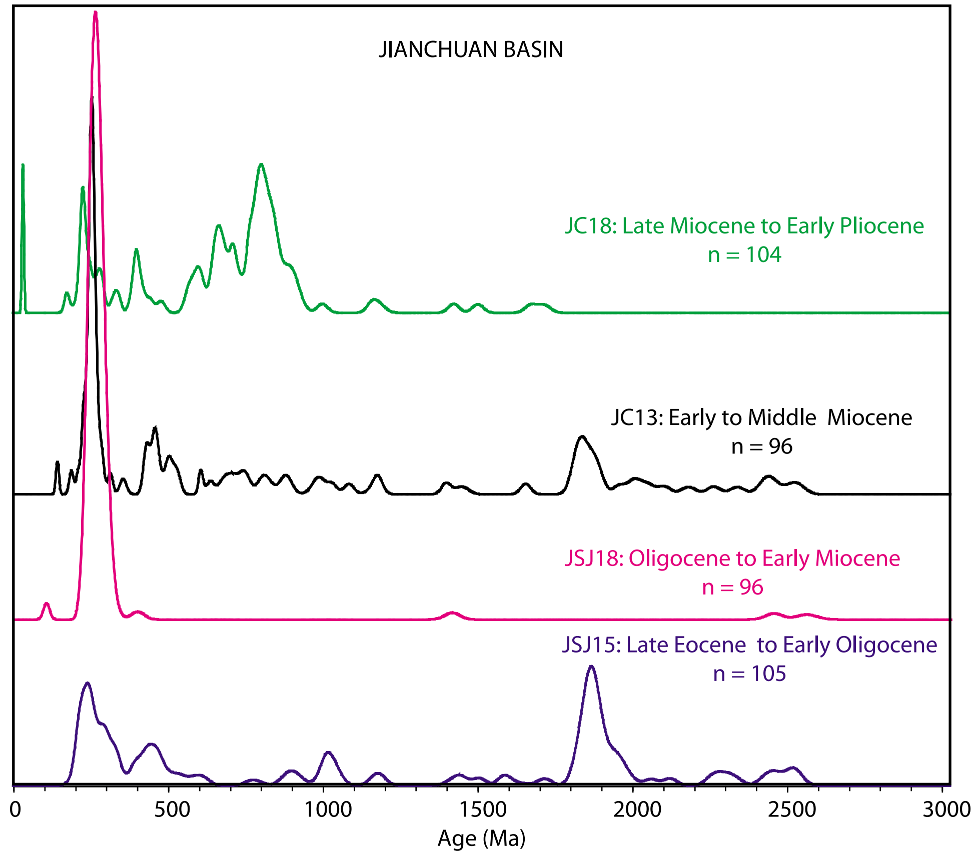

Figure 4. Plots of detrital zircon ages for each of the studied samples from the Jianchuan Basin. Plots use ages ≤10% discordant with $^{206}Pb/^{238}U$ used for ages <1000 Ma and $^{207}Pb/^{206}Pb$ for older grains.

additional analytical details are provided in the auxiliary material.[1]

4. Results and Interpretation

[9] The Upper Yangtze has its watershed in the Qiangtang Block, passes through the western Songpan-Garze Block and then runs south through the Yidun Arc including the Jinshajiang Suture Zone, while the Yalong and Dadu Rivers, which run into the Middle Yangtze River, drain the Songpan-Garze Complex (Figures 2a and 2b). Triassic rocks are present across the region but the geology of the Qiangtang-Yidun Arc contains younger rocks than the Songpan-Garze Complex, at least what has been described in the literature thus far. Most of the Upper Yangtze runs broadly N-S along the Jinshajiang Suture Zone, which contains a Devonian to Triassic sequence of marine sedimentary rocks that, like the main part of the arc, were intruded by high-K calcalkaline igneous rocks and adakites dated to between 245 and 211 Ma [*Weislogel et al.*, 2006; *Xiao et al.*, 2007; *Zhang et al.*, 2006]. Younger granitoids are also present with ages between ∼200–188 Ma and ∼105–95 Ma [*Roger et al.*, 2004; *Reid et al.*, 2007]. Modern river sands transported by the Upper Yangtze record these different sources although are mainly dominated by Mesozoic to Neoproterozoic aged zircons sourced from Jinshajiang suture zone rocks (Figure 5) that swamp the much younger ages.

[10] Figure 4 plots the age distributions of zircons from each of the sampled rocks. The oldest sample (JSJ15), from massive fluvial sandstones belonging to the Baoxiangsi Formation, has a wide range of zircon ages with major groups between 200 and 500 Ma and 1.8–2.1 Ga but lacks Mesoproterozoic grain ages between 1.4 and 1.8 Ga that would be expected if the paleo-river drained a region to the northwest, i.e., a paleo Upper Yangtze. There is also only a trace of Neoproterozic aged zircons. These differences are shown in Figure 5, which compares data from modern river sands of the

[1]Auxiliary materials are available at ftp://ftp.agu.org/apend/gc/2011gc003803.

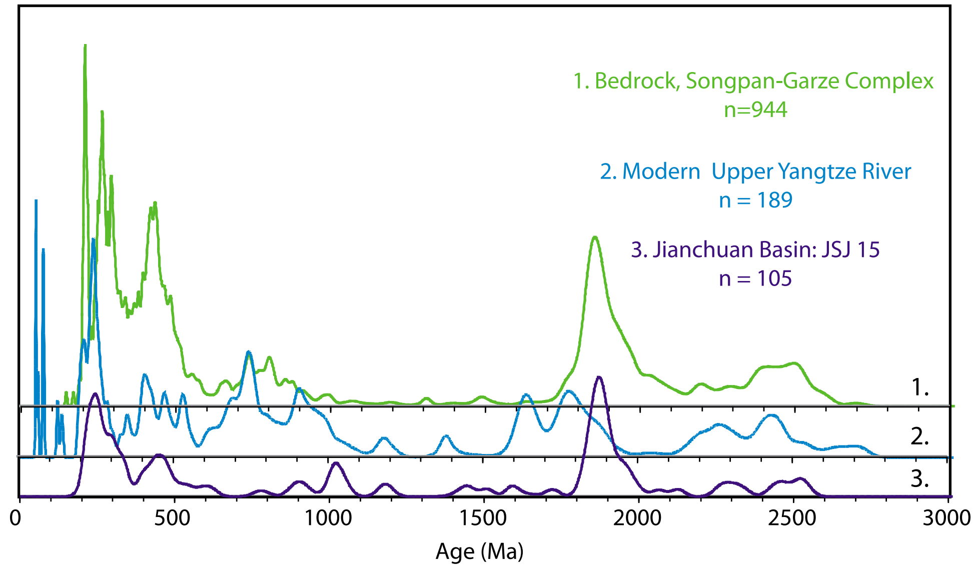

Figure 5. Comparison between zircon U-Pb ages for Paleogene sample JSJ15 from the Baoxiangsi Formation with-modern sands from the Upper Yangtze River [*Hoang et al.*, 2009; *Kong et al.*, 2009], and rocks belonging to the Songpan-Garze Complex [*Weislogel et al.*, 2006; *Xiao et al.*, 2007; *Zhang et al.*, 2006].

Upper Yangtze with the results of sample JSJ15. The modern river sands contain Neoproterozic zircons and a large group of Mesoproterozoic ages that are absent from the Baoxiangsi Formation sample. Comparison is also made in Figure 5 between sample JSJ 15 and the zircon age distribution from rocks of the Songpan-Garze Complex [*Weislogel et al.*, 2006; *Xiao et al.*, 2007; *Zhang et al.*, 2006]. Sedimentary rocks comprise most of the Songpan-Garze Complex, and were deposited in the Middle to Late Triassic by watersheds that drained from the north and south. JSJ 15 lacks c. 800 Ma zircons and this fits with stratigraphically older rocks of the Songpan-Garze Complex [*Weislogel et al.*, 2006; *Xiao et al.*, 2007; *Zhang et al.*, 2006]. The zircon age distribution for sample JSJ15 is near identical to the data from Songpan-Garze rocks (Figure 5) sourced from the North China Block [*Weislogel et al.*, 2006, Figure 3].

[11] The bulk of dated grains for the Oligocene to Middle Miocene samples JSJ18 and JC13 fall between 233 ± 17 Ma and 312 ± 22 Ma. JC13 has a small peak of proterozoic ages around 1800–1900 Ma consistent with North China block sources as seen in the Songpan-Garze rocks. Precambrian grains are rare in sample JSJ18, only 3 such grain ages (two at c. 2500 Ma one at 1400 Ma) are found. The single large age peak seen in sample JSJ18 can be explained by more restricted erosion involving Triassic igneous sources. A larger drainage would have produced a wide range of older ages as seen in the Late Miocene to Pliocene sample (JC18) which includes many grains dated to between 750 and 850 Ma, diagnostic of Yangtze Craton (South China Block) sources [*Sun et al.*, 2009; *Roger et al.*, 2010] from watersheds to the east and northeast of the basin. The absence of Mesoproterozoic and older zircon ages is also consistent with a local drainage reinforced by the presence of grains with ages of 34–35 Ma that match igneous bodies known in the area of the Jinchuan Basin and emplaced during a period of potassic igneous activity dated to between c. 40–24 Ma [*Wang et al.*, 2001; *Guo et al.*, 2005; *Xiang et al.*, 2009].To summarize, since the Late Oligocene sediment deposited by rivers that flowed through and into the Jianchuan Basin have zircon age populations consistent with erosion involving local sources that include rocks belonging to the Yidun Arc and the Yangtze Craton, part of the South China Block.

5. Discussion

5.1. Paleogene Drainage

[12] Results show that Paleogene fluvial sedimentary rocks deposited in the Jinchuan Basin have a provenance consistent with erosion of Triassic marine sedimentary rocks belonging to the Songpan-Garze Complex. The zircon age distribution for

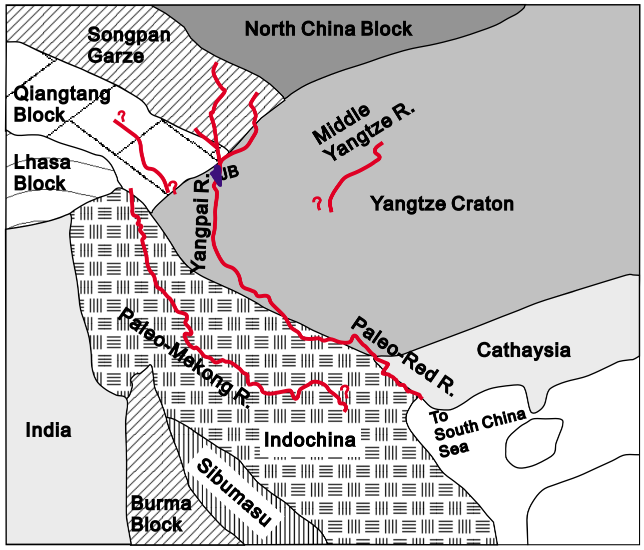

Figure 6. Cartoon to a paleo-drainage configuration for the early Palaeogene that would fit with the data described in this study. The headwaters would have been located north to northeast of the Jianchuan Basin within the Songpan-Garze Complex and lasted until the Oligocene when the drainage system changed.

sample JSJ15 closely matches Songpan-Garze rocks sourced from the North China Block. The absence of Neoproterozoic ages would fit with the erosion confined to Ladinian and Carnian aged units within the Songpan-Garze Complex [*Weislogel et al.*, 2006]. The data can be explained by rivers flowing within the Songpan-Garze Complex either from the northeast or northwest. A drainage system that had its headwaters in the northeast and not the northwest as at present would require a reverse flowing section of the upper parts of the Middle Yangtze River or its paleo equivalent. Existence of a reversed Middle Yangtze River connected to the Jianchuan Basin during the Paleogene is geographically hard to explain and does not fit with the models of *Clark et al.* [2004] that show a southwest-flowing Middle Yangtze River joining the Red River far to the southeast of the Jianchuan Basin prior to its capture by the Upper Yangtze (Figure 1). But, it has also been argued that capture of the Middle Yangtze and Sichuan Basin by the east-flowing Lower Yangtze took place in the Eocene on the basis of thermochronometry data from the Three Gorges area that show significant rock uplift and gorge incision started between 45 and 40 Ma [*Richardson et al.*, 2010] overlapping with the onset of erosion across the Sichuan Basin at ~40 Ma [*Richardson et al.*, 2008]. A study by *Kong et al.*, [2009] suggested that flow reversal of the Middle Yangtze was a more recent development caused by local fault movements in the Quarternary. Such interpretations seem contrary but it is important to keep in mind that river captures were progressive and that the Yangtze River likely grew by amalgamation of rivers and segments of rivers. Our results suggest that one stage in this process involved a paleo Yalong River or extended Yangpai River that extended further north into the Songpan-Garze Complex (Figure 6). The data do not require a connection to the Upper Yangtze at this time i.e., early Paleogene. Although the zircon data do not prove if the main source came from either the northeast or northwest, or both, we do note that modern river sands transported by the Upper Yangtze are dominated by Mesozoic to Neoproterozoic aged zircons sourced from Jinshajiang suture zone rocks and notably lack populations of zircons between 1.85 and 1.95 Ga [*Hoang et al.*, 2009] (Figure 5). On this basis there is a better match to sources within the northeastern part of the Songpan-Garze Complex.

[13] The results (JSJ15) show that a drainage connection to the distant Songpan-Garze Complex was less important by the Late Paleogene and that sedimentation within the Jianchuan Basin thereafter involved greater contributions from more local sources. These changes began in the Oligocene. Independent studies also favor this timing for major rivers captures. Nd isotope studies of Eocene sedimentary rocks deposited in the Hanoi Basin, Vietnam showed strongly negative εNd values considered to be associated with erosion of the Yangtze Craton [*Clift et al.*, 2006]. The strongly negative εNd values contrasted with less negative

εNd values from Paleogene rocks in the Yinggehai Basin, South China Sea [*Yan et al.*, 2007] the final repository for sediment supplied by the Red River and any paleo-equivalent that overspilled from the Hanoi Basin. The less negative εNd values were measured on core samples from close to Hainan Island and reflect this local source. A later mass balance study examined the volume of sedimentary rock deposited in Yinggehai Basin since 30 Ma and found that the sediment volumes could be explained by a paleo catchment similar in area to that of the modern Red River with the addition of minor inputs from erosion of Hainan Island [*Yan et al.*, 2011], providing further confirmation that any expanded paleo-Red River drainage (if any ever existed) must have predated the Oligocene.

5.2. Mechanism of River Re-organization

[14] River capture or diversion events are often associated with regional tectonics. Within SW China changes in regional stress accommodation saw a switch from strike-slip faulting in the Paleogene to regional surface uplift in the Neogene (see section 2 above). As stated earlier either or both of these phases of deformation may have contributed to changes in regional drainage therefore our sampling strategy covered this time interval. Our results show that a large river drained the Songpan-Garze Complex and may have flowed to the southwest or southeast passing through the area of the Jianchuan Basin during the early Palaeogene until the Oligocene when this connection ended. Such timing favors a connection between drainage re-organization and the deformation associated with strike-slip faulting. Left-lateral ductile shearing across the region accommodated clockwise rotation and continental extrusion of Indochina–SE Asia and was caused by the collision and indentation of India into Asia [*Molnar and Tapponnier*, 1975]. This resulted in a series of NW-SE aligned metamorphic complexes (Xuelong Shan, Diancang Shan, Ailao Shan) in Yunnan Province that record ductile shear between ~32–22 Ma [*Searle et al.*, 2010]. An unconformity, seen in the Jianchuan Basin between the 'Eocene' series and Oligocene rocks [*Xiang et al.*, 2007; *Zhang et al.*, 2010] provides the link between this regional deformation and changes in drainage.

6. Conclusions

[15] Detrital zircon data from sedimentary rocks deposited in the Jianchuan Basin identified a change in depositional systems from a large river in the Eocene-Early Oligocene that extended into the Songpan-Garze Complex, switching to more local sources, which were dominant by the Neogene. Results are consistent with independent studies that found no evidence to support the existence of a large river system, at least not since the Oligocene. By contrast to the geomorphology models, the zircon results indicate a paleo-drainage with a large southward flowing river with its headwaters located in the northeast or northwest. Timing of loss of this large river coincided with left-lateral ductile shearing across the region recorded by an unconformity within the basin stratigraphy suggesting uplift at that time. The changes in regional drainage outlined in this paper should be seen as one part of a long series of river captures that continued throughout the Cenozoic in response to local tectonics and regional tilting.

Acknowledgments

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