Source to sink relations between the Tian Shan and Junggar Basin (northwest China) from Late Palaeozoic to Quaternary: evidence from detrital U-Pb zircon geochronology

Wei Yang,* Marc Jolivet,† Guillaume Dupont-Nivet,*‡ Zhaojie Guo,* Zhicheng Zhang* and Chaodong Wu*

*Key Laboratory of Orogenic Belts and Crustal Evolution, Ministry of Education, School of Earth and Space Sciences, Peking University, Beijing, China
†Geosciences Rennes, Université Rennes 1, Rennes, France
‡Faculty of Geosciences, Utrecht University, Utrecht, The Netherlands.

ABSTRACT

The tectonic evolution of the Tian Shan, as for most ranges in continental Asia is dominated by north-south compression since the Cenozoic India-Asia collision. However, precollision governing tectonic processes remain enigmatic. An excellent record is provided by thick Palaeozoic – Cenozoic lacustrine to fluvial depositional sequences that are well preserved in the southern margin of the Junggar Basin and exposed along a foreland basin associated to the Late Cenozoic rejuvenation of the Tian Shan ranges. U/Pb (LA-ICP-MS) dating of detrital zircons from 14 sandstone samples from a continuous series ranging in age from latest Palaeozoic to Quaternary is used to investigate changes in sediment provenance through time and to correlate them with major tectonic phases in the range. Samples were systematically collected along two nearby sections in the foreland basin. The results show that the detrital zircons are mostly magmatic in origin, with some minor input from metamorphic zircons. The U-Pb detrital zircon ages range widely from 127 to 2856 Ma and can be divided into four main groups: 127–197 (sub-peak at 159 Ma), 250–379 (sub-peak at 318 Ma), 381–538 (sub-peak at 406 Ma) and 543–2856 Ma (sub-peak at 912 Ma). These groups indicate that the zircons were largely derived from the Tian Shan area to the south since a Late Carboniferous basin initiation. The provenance and basin-range pattern evolution of the southern margin of Junggar Basin can be generally divided into four stages: (1) Late Carboniferous – Early Triassic basin evolution in a half-graben or post-orogenic extensional context; (2) From Middle Triassic to Upper Jurassic times, the southern Junggar became a passively subsiding basin until (3) being inverted during Lower Cretaceous – Palaeogene; (4) During the Neogene, a piedmont developed along the northern margin of the North Tian Shan block and Junggar Basin became a true foreland basin.

INTRODUCTION

The Junggar Basin, situated north of the Tian Shan ranges (Fig. 1), holds sub-continuous record of the still controversial tectonic evolution of this part of continental Asia. Although continental detrital sedimentation initiated in late Palaeozoic time, the basin has been rejuvenated as a foreland basin since the Late Cenozoic period due to north-south compression induced in this region by the effects of the India-Asia collision (Burckle & Royden, 1991; Avouac et al., 1993; Lu et al., 1994; Yin et al., 1998). Thick accumulations of sediments derived mostly from the Tian Shan area form the Mesozoic to Quaternary lacustrine to fluvial depositional sequences that are well preserved and exposed in the southern margin of the Junggar Basin (Hendrix, 2000; Fang et al., 2005; Fang et al., 2006a; Wu et al., 2006; Charreau et al., 2009a). The tectonic evolution of the Junggar Basin underwent different stages since the latest Palaeozoic, and this evolution is still largely debated. The first divergence between authors concerns the tectonic setting at the basin initiation generally attributed to be Permian in age. Some studies support the idea that the Permian basin was a foreland basin (Liu et al., 1994, 2000; Carroll et al., 1995; Chen et al., 2001; Jia et al., 2003; He et al., 2004), whereas others considered it as a transtensional basin (Allen et al., 1995; Cai et al., 2000; Chen et al., 2005). Finally, Fang et al.
(2006c) considered that the Junggar Basin formed as a fault-controlled depression during a Permian extensional tectonic episode. Another important, and still enigmatic issue is the Mesozoic setting of the Junggar Basin with contrasting hypothesis involving: an extensional basin (Li & Chen, 1998; Liu et al., 2000), a continental depression basin (Xu et al., 1997a, b; Chen et al., 2002; Jolivet et al., 2010), or a foreland basin associated to the collision of the Qiangtang terrane to the south (Hendrix et al., 1992; Zhang et al., 1999; Chen et al., 2002). Several studies showed that the Tian Shan ranges existed as a positive physiographic feature during the Mesozoic (Hendrix et al., 1992; Dumitru et al., 2001; Jolivet et al., 2010; Chen et al., 2011). However, Hendrix (2000) suggested that during the Early-Middle Jurassic, the range could not be considered as a towering topography significantly separating climate patterns. This suggests that the Mesozoic Tian Shan, together with its adjacent regions, may have been under an extensional tectonic setting resulting from post-orogenic relaxation after the Permian collision (Guo et al., 2005, 2006; Fang et al., 2006a). These contrasting hypotheses put forward the necessity to look for more effective evidences to correctly understand the tectonic setting of the Junggar Basin at different stages since its late Paleozoic inception.

Detrital zircon U-Pb chronology has become a powerful tool for provenance and geodynamic studies (e.g. Fedo et al., 2003; Gehrels et al., 2003; Prokopiev et al., 2008). The systematic study of variations through time of characteristic detrital zircon ages populations obtained from sedimentary sequences in basins can reflect the changes in basin-range relationships. The complete (or near complete) late Paleozoic to Quaternary lacustrine to alluvial fan sedimentary series are exposed along the southern margin of the Junggar Basin. A detailed study of the U-Pb detrital zircon age populations in those series may thus provide detailed information on the evolution of the sediment sources and the palaeo-drainage system. This study, 14 sandstone samples (Fig. 2) from upper Palaeozoic to Quaternary strata were collected along two sections on the southern margin of the Junggar Basin in order to perform U-Pb (LA-ICP-MS) dating of detrital zircons. The results are used to discuss the behaviour of the Junggar Basin through time, as well as the characteristic phases of interaction between the basin and the Tian Shan.

**GEOLOGICAL SETTING**

**General evolution of the Tian Shan**

The present-day Tian Shan extends through western China, Kazakhstan and Kyrgyzstan and represents an important part of the Central Asian Orogenic Belt (CAOB) (see for example Windley et al., 2007 for a complete synthesis of the evolution of the CAOB). The
The following summary of the geological history of Tian Shan, is supported by a review of available U/Pb ages on zircons obtained for various granitoids and host rocks presented in Fig. 1.

The Tarim – South Tian Shan (STS) and Central Tian Shan blocks (CTS) collided during Late Devonian – Early Carboniferous. This accretion was followed during Late Carboniferous – Early Permian by the collision of the newly formed Tarim – Central Tian Shan terrane with a series of late Palaeozoic island arcs now forming the Northern Tian Shan (NTS) (e.g. Huang et al., 1980; Wang et al., 1990; Allen et al., 1992; Biske & Seltmann, 2010; Han et al., 2010; Charvet et al., 2011). The CTS basement is mainly composed of metamorphic Proterozoic series extensively intruded by granitic plutons ranging in age between 380 and 490 Ma (Zhou et al., 2001; Han et al., 2004; Glorie et al., 2010). The second accretion episode is marked in CTS and NTS by the occurrence of numerous Early Permian (295–280 Ma from U/Pb on zircons) post-collisional A-type granites that cross-cut the Palaeozoic structures (e.g. Konopelko et al., 2007; Gao et al., 2009; Wang et al., 2009; Glorie et al., 2010). Zircon (U-Th)/He ages from the CTS confirm the occurrence of a major cooling phase in Early Permian (Jolivet et al., 2010). The compressive structures that formed during those various episodes of accretion were then reworked by late Palaeozoic strike-slip shear zones such as the Main Tian Shan Shear Zone (MTSZ) that separates the CTS from the NTS (e.g. Allen et al., 1995; Laurent-Charvet et al., 2002, 2003). Numerous Permian 40Ar/39Ar and K–Ar ages on muscovite and biotite from the MTSZ or similar major structures indicate that this shearing phase probably ended in Late Permian or Early Triassic (e.g. Shu et al., 1999; Chen et al., 1999; Laurent-Charvet et al., 2002).

The Tian Shan area was then reactivated by the successive terrane collision onto the south Asian margin during the Early Mesozoic (Hendrix et al., 1992; Dumitr et al., 2001; Greene et al., 2005; Lu et al., 2010; Jolivet et al., 2010). Apatite fission track and (U-Th)/He data from the CTS and the southern edge of the NTS demonstrate that

Fig. 2. U-Pb concordia diagrams for zircon grains of the 14 sandstone samples.
the Permian exhumation phase has been subsequently overprinted by an Early Jurassic cooling phase (Dumitru et al., 2001; Jolivet et al., 2010) probably related to the far-field effects of the final collision between the Qintang and Kunlun blocks (e.g. Jolivet et al., 2001; Roger et al., 2010, 2011).

Strong erosion during the Triassic and Early Jurassic initiated general peneplanation of the Tian Shan region that was probably well-evolved by Early-Middle Jurassic time (Shu et al., 2004). Although this erosional phase has been widely recognized throughout Central Asia (e.g. Jolivet et al., 2007, 2009, 2010, 2011; Vassallo et al., 2007), apatite fission track data from the NTBs and coarse sediments in surrounding basins (Yili and Junggar) suggest that recurrent, small magnitude vertical movements occurred during Late Jurassic – Early Cretaceous time (Dumitru et al., 2001; Jolivet et al., 2010) implying that peneplanation was probably incomplete. De Grave et al. (2004, 2007) and Glorie et al. (2010) report similar observations in the Kyrgyz Tian Shan. Sedimentological data within the surrounding basins indicate that by Late Jurassic – Cretaceous, and possibly onwards, the largely peneplaned Tian Shan region may have been affected by an extension induced by post-orogenic relaxation (Shu et al., 2004; Guo et al., 2005, 2006; Fang et al., 2006a).

Finally, during late Cenozoic, the Tian Shan area has again been reactivated by the distant effects of the India-Eurasia collision, leading to the formation of the actual intracontinental orogenic belt (Molnar & Tapponnier, 1975; Tapponnier & Molnar, 1977, 1979; Burchfiel & Royden, 1991; Avouac et al., 1993; Lu et al., 1994; Yin et al., 1998; Burchfiel et al., 1999; Allen et al., 1999; Dumitru et al., 2001; Guo et al., 2003; Buslov et al., 2004, 2007; Jolivet et al., 2010).

General evolution of the Junggar Basin

The Junggar Basin is divided into six structural units (e.g. Li, 1993; Qiu et al., 2008). The deepest one, lying along the northern edge of the Tian Shan, is the Southern depression that collected about 16 km of sediments since Permian time. Its basement is mainly composed of Carboniferous volcanic rocks. The Permian magmatism occurring in the Junggar Basin and its adjacent regions is generally attributed to a tectonic and continental rift tectonic setting (Kovalenko et al., 1996; Han et al., 1997; Jahn et al., 2000a, b; Jahn, 2004) for which clear evidence is reported from the Bogda region, the eastern Junggar Basin and the Turpan-Hamin Basin (Han et al., 1999; Wartes et al., 2002; Shu et al., 2004). However, as already exposed in the introduction, the initiation of the Junggar basin is still largely discussed both in terms of timing and initiating mechanism. If most of the authors agree that the basin initiated during the Permian, some studies consider that it could have evolved as a half-graben during Late Carboniferous (e.g. Qiu et al., 2005).

Following inception, many authors consider the Mesozoic Junggar Basin as a foreland basin (Hendrix et al., 1992; Graham et al., 1993; Zhang et al., 1999; Chen et al., 2002), with the Tian Shan ranges existing as a positive physiographic feature at least during Triassic and Jurassic times (Hendrix et al., 1992; Dumitru et al., 2001). However, based on the widespread Lower and Middle Jurassic series including well-developed coal strata and concentrated thick coal seams, many others consider the tectonic setting as a thermally subsiding basin associated to a palaeo-range which was progressively eroded away without much tectonic activity (Dumitru et al., 2001; Fang et al., 2005; Vassallo et al., 2007; Jolivet et al., 2007, 2010; Glorie et al., 2010).

The present-day southern margin of the Junggar Basin exposes three rows of late Cenozoic fault-propagation folds formed successively towards the north in the foreland (Avouac et al., 1993; Burchfiel et al., 1999; Deng et al., 2000; Lu et al., 2010; Li et al., 2010, Li et al., 2011a, b). These folds are referred from south to north as the piedmont belt, the Huoerguosi-Manas-Tugulu belt and the Dushanzi-Anjihai belt (Fig. 3). The southernmost piedmont belt consists of several anticlines formed during Late Miocene to Pliocene, such as the Qigu anticline (Avouac et al., 1993; Lu et al., 2010; Li et al., 2010). The northernmost Dushanzi-Anjihai anticlines evolved during the Late Pliocene-Early Pleistocene (Avouac et al., 1993). This Neogene tectonic activity induced uplift and erosion of the Mesozoic sedimentary series along the southern edge of the Junggar Basin (Fig. 3).

STRATIGRAPHY AND SEDIMENTARY CHARACTERISTICS

The studied Dong Datang and Taxi He sections (Fig. 3) have been chosen for their exceptional preservation and exposure of the Permian to Quaternary sedimentary series along the southern margin of the Junggar Basin (Fang et al., 2007). For a comprehensive understanding of the basin evolution, a summary of the observed and published descriptions of lithologies, depositional systems, palaeocurrent measurements and general environmental cycles through time is presented (Fig. 4).

The Permian series consist of the Aerbaysai Formation, the Quanzijie Formation and the Wutonggou Formation, which are mainly composed of tuffaceous conglomerates, breccia, andesite porphyry and pebbly coarse-grained sandstones. The depositional environments evolved from an alluvial fan – braided river system in the Aerbaysai Formation to a braided river and delta system in the Upper Permian Wutonggou Formation indicating a slight retrogradation phase (note that in this study, as the Junggar basin is not connected to the sea, we use the terms progradation and retrogradation with respect to the position of the lacustrine environment. For example, a complete progradation sequence will correspond to a progressive shift in depositional environment from lake sediments towards coarse alluvial fan sediments).
Fig. 3. Geological setting of the southern margin of the Junggar Basin with samples locations (map modified from Li et al., 2011a, b).

The Triassic series can be divided into the Shangcangfanggou Group and the Xiaoquangou Group. The sediments are brown-grey-coloured mudstones, argillaceous siltstones, litharenites, and sandy mudstones. The Lowermost Shangcangfanggou Group is characterized by typical braided river to deltaic sandy conglomerates (Wu et al., 2006) whereas the Xiaoquangou Formation was deposited in an alluvial plain to shallow lacustrine system. The facies evolution towards a lacustrine environment reinforces the general retrogradation phase initiated in the Permian. However, Hendrix et al. (1992) report alluvial and braided river facies in the Upper Triassic series of the nearby Manas section suggesting lateral facies variations probably due to local topography. Palaeocurrent measurements (Hendrix et al., 1992) indicate an E–W drainage system in the Upper Triassic (Fig. 4).

The Jurassic series, showing a maximum thickness over 4000 m, are broadly distributed with both the local depocenter and subsidence centre located next to the Changji area (Fig. 1; Fang et al., 2005). The sequence consists of the Lower Jurassic Badaowan Formation and Sangonghe Formation, the Middle Jurassic Xishanyao Formation and Toutunhe Formation, and finally the Upper Jurassic Qigu Formation and Kalazha Formation (Fang et al., 2005, 2006a, 2007; Wu et al., 2006).

The Badaowan Formation, lying unconformably on the Triassic series, is composed of mudstones interbedded with grey sandstones in the lower part and interbedding of sandy mudstones and sandstones (containing thin coal layers or coal streaks) in the upper part. These sediments were deposited in a braided river to shallow lacustrine environment (Fig. 4). Palaeocurrents are mostly oriented towards the NE but Hendrix et al. (1992) report NNW to W palaeocurrent directions in the Manas section.

The following Sangonghe Formation is mainly composed of grey-green mudstones and sandstones containing thin coal streaks and coal layers. The facies correspond to alluvial plain and lacustrine deposits. Palaeocurrents are oriented towards the north in our section and towards the W–NW in the Manas section (Hendrix et al., 1992). During the Lower Jurassic, the Junggar Basin underwent two large-scale lacustrine transgressions (Fang et al., 2005), which are consistent with the general retrogradation phase observed in our data.

The thickness of the Xishanyao Formation is the largest, and may locally exceed 1000 m. Grey-green sandstones and mudstones rich in coal layers and coal streaks which can be regarded as the characteristics of lake swamp deposits are ubiquitous in that formation. Thick coal layers are often found in the middle and lower parts. Palaeocurrents are oriented towards the NNW in our section and towards the NNE in the Manas section (Hendrix et al., 1992). The Chepaizi-Mosuowan low uplift, located in the northern side of the southern margin of the Junggar Basin (north of Fig. 5), began to develop during the depositional period of the Xishanyao Formation. However, the general northward palaeocurrents direction indicates that the source area was still to the south and that the Chepaizi-Mosuowan uplift had little influence on the established drainage system that provided sediments to this area of the basin.

The Middle Jurassic Toutunhe Formation is mainly composed of mottled mudstones, sandy mudstones and sandstones, representing a braided-river sedimentary environment. This shift between a mainly lacustrine environment in the Xishanyao Formation to a braided river environment marks the onset of a progradation phase. The amount of red-banded sediment occurring in the Xishanyao formation increases up section, indicating that the climate became gradually dry (Fang et al., 2005). Although the Chepaizi-Mosuowan low uplift developed further during that time, the northwestward-directed
palaeocurrents indicate that this uplift still has little effect on the drainage system in the studied area.

There is an obvious local unconformity between the underlying Toutunhe Formation and the overlying Upper Jurassic Qigu Formation (although this one is not observed by Hendrix et al. (1992) in the Manas section). The Qigu sediments are mostly composed of interbedding of brown-purple mudstones and sandstones, with the mudstone mainly restricted to the upper part, and thin-bedded limestone interbedded at the bottom. These sediments were deposited in a shallow lacustrine to alluvial plain environment, with palaeocurrents still oriented towards the NW in the Manas section where the Qigu Formation reaches its greatest thickness (about 683 m) (Hendrix et al., 1992).

The Upper Jurassic Kalazha Formation is formed by a typical brown-red thick-bedded conglomerate, also called the ‘Kalazha red dyke’. This conglomerate corresponds to a large alluvial fan deposit representing the last stage of the progradation event initiated during the Middle Jurassic Xishanyao Formation (Fig. 4). Palaeocurrents in the Manas section are oriented NW or NE (Hendrix et al., 1992). During the sedimentation of the Qigu and Kalazha formations, the Chepaizi-Mosuowan uplift was still continuously active (Fang et al., 2005). The slight spread in palaeocurrent directions (Fig. 4) may indicate a possible effect of this growing relief on the drainage pattern. However, the source area of the sediments is still situated towards the south.

The Cretaceous series in the southern margin of the Junggar Basin, consists in the Tugulu Group and the Donggou Formation. The sediments of the Tugulu Group are mainly composed of grey-green mudstones interbedded with sandstones deposited in a lacustrine environment. Palaeocurrents from the Manas section are again NW or NE directed (Hendrix et al., 1992). However, measurements of palaeocurrent directions in lacustrine environments should only be considered as
indicative. The Tugulu Group marks the onset of a new progradation phase that initiated from the sharp change between the alluvial fan of the Kalazha Formation and the lacustrine environment of the Lower Tugulu Group. The Donggou Formation is mainly composed of grey-green mudstones, sandstones and conglomerates corresponding to alluvial to braided river system. Palaeo-currents directions are mainly unchanged.

The Palaeogene series consist of the Ziniquanzi Formation, the Anjihaihe Formation and the Shawan Formation. Unfortunately no palaeocurrent measurements are available for the Tertiary section. The Ziniquanzi Formation is mainly characterized by purplish-red mudstones and sandstones corresponding to a lacustrine environment. The Anjihaihe Formation is mainly composed of mottled mudstones and sandy mudstones interbedded with sandstones, which are again characteristic of lacustrine environments (Fig. 4). The Shawan Formation consists in reddish-brown pelitic siltstones, mudstones and glutenite interlayers deposited in a lacustrine to alluvial plain environment. The lake depth reached its maximum during the sedimentation of the Anjihaihe Formation (Fang et al., 2006b; Charreau et al., 2008). However, this major lacustrine phase seems to represent an isolated event within a general progradation phase that initiated in the Lower Cretaceous. Although we have no constraints on the forces that drive these changes in depositional environments, climate variations associated to a generally low tectonic activity may induce the observed recurrent changes between lacustrine and alluvial plain systems.

The Neogene series are divided into the Taxihe Formation and the Dushanzi Formation, which are both characterized by their great thickness (locally exceed 2000 m). The Taxihe Formation is mainly composed of reddish-brown sandy conglomerates and pelitic sandstones deposited in an alluvial plain environment. The Dushanzi Formation contains brown sandy mudstones, fine graywackes and conglomerates characteristic of a braided river system. Finally, the Quaternary Xiyu Formation is characterized by a typical conglomerate, interbedded with grey medium-grained litharenite and sandy mudstone (BGMRXUAR [Bureau of Geology and Mineral Resources of Xinjiang Uygur Autonomous Region], 1978, 1993, 2008; Wang et al., 2000a; Fang et al., 2007; Charreau et al., 2009b). It corresponds to a series of major alluvial fan deposits, which represent the maximum of the general progradation phase that initiated in Early Cretaceous.

**Sampling and Analytical Methods**

Fourteen sandstone samples ranging in age from the latest Palaeozoic to the Quaternary were collected from two field sections to the southern Junggar Basin (Fig. 4). Nine samples of upper Palaeozoic-Mesozoic strata were selected from the western Dong Datang profile, and five samples of Cenozoic strata from the eastern Taxi He profile (Fig. 3). Due to the short distance separating the two profiles, the sources of the sediments in both of them may generally be considered as similar. The major characteristics of the samples are described in Table 1.

Detrital heavy minerals were separated from sandstone samples by the standard procedures used for mineral separation (Li et al., 2004). This work was conducted by the Chengxin Geology Service Co. Ltd, Langfang, Hebei Province, China. Zircons were specifically extracted using heavy liquids and magnetic techniques and finally purified by hand picking and careful identification under a binocular microscope. A quantity of zircon grains (generally more than 200 grains) were randomly selected with a steel pin

<table>
<thead>
<tr>
<th>System</th>
<th>Formation/group</th>
<th>Sample code</th>
<th>Lithofacies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quaternary</td>
<td>Xiyu Fm.</td>
<td>XJ09-021</td>
<td>Medium-grained litharenite contained in sandy conglomerate alternating beds of the Xiyu conglomerate</td>
</tr>
<tr>
<td>Neogene</td>
<td>Dushanzi Fm.</td>
<td>XJ09-017</td>
<td>Medium-coarse-grained sandstones contained in a sandstone lens, associated with interbedded sand and gravel, in which the conglomerates are dominant</td>
</tr>
<tr>
<td>Palaeogene</td>
<td>Taxihe Fm.</td>
<td>XJ09-003</td>
<td>Grey-green coarse-grained sandstones</td>
</tr>
<tr>
<td></td>
<td>Anjihaihe Fm.</td>
<td>XJ09-010</td>
<td>Khaki medium-grained sandstones</td>
</tr>
<tr>
<td>Upper Cretaceous</td>
<td>Donggou Fm.</td>
<td>XJ10-015</td>
<td>Grey-green coarse-grained sandstones</td>
</tr>
<tr>
<td>Lower Cretaceous</td>
<td>Qingshuimei Fm.</td>
<td>XJ10-016</td>
<td>Grey-green coarse-grained sandstones</td>
</tr>
<tr>
<td>Upper Jurassic</td>
<td>Qigu Fm.</td>
<td>XJ09-100</td>
<td>Reddish-brown coarse-grained sandstones</td>
</tr>
<tr>
<td>Middle Jurassic</td>
<td>Toutune Fm.</td>
<td>XJ10-018</td>
<td>Grey-green coarse-grained sandstones</td>
</tr>
<tr>
<td>Lower Jurassic</td>
<td>Badaowan Fm.</td>
<td>XJ09-097</td>
<td>Yellow-green pebbly coarse-grained sandstones</td>
</tr>
<tr>
<td>Middle-Upper Triassic</td>
<td>Xiaosuoqiong Fm.</td>
<td>XJ10-011</td>
<td>Grey-green pebbly coarse-grained sandstones</td>
</tr>
<tr>
<td>Lower Triassic</td>
<td>Shangcangfanggou Group</td>
<td>XJ09-094</td>
<td>Grey coarse-grained sandstones associated with purplish red medium-grained sandstones</td>
</tr>
<tr>
<td>Upper Permian</td>
<td>Wutonggou Fm.</td>
<td>XJ10-009</td>
<td>Mottled pebbly coarse-grained sandstones</td>
</tr>
<tr>
<td>Lower Permian</td>
<td>Aerbasiay Fm.</td>
<td>XJ09-092</td>
<td>Mottled pebbly coarse-grained sandstones within volcanic-sedimentary sequences in the lower sub-formation</td>
</tr>
</tbody>
</table>
and mounted on adhesive tape then enclosed in epoxy resin and polished to yield a smooth flat internal surface (slice). After being photographed under reflected and transmitted light, the samples were prepared for cathodoluminescence (CL) imaging, to choose potential internal target sites for U-Pb dating (Yuan et al., 2002; Long et al., 2010).

Cathodoluminescence (CL) imaging was carried out using a HITACHI S3000-N Scanning Electronic Microscope (Hitachi, Tokyo, Japan) at the Institute of Geology, Chinese Academy of Geological Sciences. CL images of typical zircon grains are presented in Appendix S2. Laser Ablation–Inductively Coupled Plasma–Mass Spectrometer (LA-ICP-MS) U-Pb dating was conducted on an Agilent 7500a ICP-MS (Agilent, Santa Clara, USA) connected to a 193 nm Excimer laser ablation system of American New Wave UP 193 SS (New Wave, Pennsylvania, USA) at the China University of Geosciences, Beijing. The operating parameters were as follows: Ar plasma gas flow rate was 1.13 l/min, RF (radio frequency) power was 1350W, and elemental integral time was 20 ms for U, Th, Pb and 15 ms for other elements (Si, Ti and Zr). Helium with a flow rate of 0.7 l/min was used as the carrier gas to enhance the transport efficiency of the ablated material. The spot diameter was 36 and 25 μm. The analytical laser frequency was 10Hz, and each analysis consisted in 5 s predenudation and 45 s signal acquisition. The GLITTER 4.4 software (China University of Geosciences, lab. of Prof. Y.S. Liu, Beijing, China) was used to calculate the U-Pb isotope ratios and element contents. Age calculations, plotting of relative probability and concordia diagrams were made using ISOPLOT (version3.0) (Ludwig, 2003). Standard zircon Tomorrow (Black et al., 2003; Qi et al., 2005) was used as an external standard for correction of isotopic ratios to calculate U-Pb ages, and zircons Qinghu and 91500 (Wiedenbeck et al., 1995) were the monitoring standards. For elemental concentration analysis, NIST610 was the external standard, and 29Si was the internal standard. Meanwhile, NIST612 and NIST614 were used as the monitoring standard. The common-Pb correction was performed following the method described by Andersen (2002). A detailed description of the technical procedure is given in Yuan et al. (2004).

For usual U-Pb (LA-ICP-MS) dating of detrital zircons, about 80–120 grains for each sample can meet the requirements of statistical analysis of basic age distribution (Andersen, 2005). In this study, except for sample XJ10-009, 100 grains from each sample were selected randomly for analysis such that, the results should reflect the provenance characteristics. Those ages with discordance degree >10% were excluded from analysis (Gehrels et al., 2003; Prokopiev et al., 2008). Isotopic ages with errors and related raw data are listed in full as Appendix S1.

**RESULTS**

The various zircon age groups and the corresponding statistical data for every sample are shown in Table 2.

### Table 2. Summary of the various age groups and the corresponding statistical data for the 14 samples

<table>
<thead>
<tr>
<th>Sample code</th>
<th>Main detrital zircon age groups (Ma)</th>
<th>Number of grains in that group</th>
<th>% of total zircon pop.</th>
<th>Number of effective data points</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Palaeozoic samples</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>XJ09-092</td>
<td>280–373</td>
<td>46–1500</td>
<td>3</td>
<td>3.1</td>
</tr>
<tr>
<td>XJ10-009</td>
<td>250–362</td>
<td>9</td>
<td>30.0</td>
<td>30</td>
</tr>
<tr>
<td>XJ09-097</td>
<td>434–508</td>
<td>5</td>
<td>16.7</td>
<td></td>
</tr>
<tr>
<td>XJ09-094</td>
<td>624–2553</td>
<td>16</td>
<td>53.3</td>
<td></td>
</tr>
<tr>
<td><strong>Mesozoic samples</strong></td>
<td></td>
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**Palaeozoic samples**

A total of 100 zircon grains were measured from Lower Permian sample XJ09-092 collected from the Aerbasayi
Formation, and 97 effective data points were obtained. U-Pb ages range from 280 to 1500 Ma, with 94 ages ranging from 280 to 373 Ma (Fig. 5). Most of these 94 crystals are characterized by relatively distinct oscillatory zoning in CL images (see Appendix S2), indicative of a magmatic origin, whereas the rest mostly show faint zoning in CL images, suggesting a metamorphic origin (Hanchar & Rundnick, 1995; Hoskin & Black, 2000; Corfu et al., 2003). The other ages are 456–460 (two grains) and 1500 Ma (one grain) respectively. These zircon grains all show oscillatory zoning indicative of a magmatic origin. The Th/U ratios of the 97 zircon grains range from 0.4 to
Due to the small amount of grains available in sample XJ10-009 (Upper Permian Wutonggou Formation), only 31 zircon grains satisfied the test conditions, and 30 effective data points were obtained. U-Pb ages range from 250 to 2553 Ma, and can be divided into three groups: 250–362 Ma (nine grains), 434–508 Ma (5 grains) and 624–2553 Ma (16 grains). The 14 zircons ranging in age from 250 to 508 Ma are dominantly characterized by oscillatory zoning in CL images (see Appendix S2), indicative of a magmatic origin. The remaining grains, ranging in age from 624 to 2553 Ma, mostly show the characteristics of metamorphic zircons. The Th/U ratios of the 31 zircon grains vary from 0.16 to 1.32, significant decrease compared to the sample XJ09-092 due to an increase in the proportion of metamorphic zircons. Again, due to the small number of analysed crystals, the age populations derived from this sample are simply indicative and maybe have no real statistical meaning.

**Mesozoic samples**

One hundred zircon grains were randomly selected from each of the seven samples of Lower Triassic (Shangcangfenggou Group) to Upper Cretaceous (Donggou Formation). Between 100 and 97 effective data points were obtained from these samples (Table 2).

For the previous Palaeozoic samples, the age groups are defined from the age of the series forming the range: the Mesozoic ages; the late Palaeozoic ages corresponding to the late Palaeozoic magmatic belt (the Upper limit is 250 Ma, the boundary between Permian to Triassic, and the Lower limit is 380 Ma, corresponding to the final emplacement of the granitic plutons in CTS (380–490 Ma); the early and middle Palaeozoic ages partly corresponding to the Palaeozoic magmatic rocks in the CTS (380 Ma to 542 Ma); and finally the Precambrian ages.

The U-Pb ages from the seven samples range from 127 to 2852 Ma, and can be mainly divided into four groups as follow: 127–183 Ma, 250–379 Ma, 382–538 Ma and 543–2852 Ma. In addition, a minority of ages range from 207 to 249 Ma (24 grains) (Fig. 5). The zircons yielding an age between 127 and 183 Ma mainly appear in the samples from the Middle Jurassic Toutunhe Formation, the Upper Jurassic Qigu Formation, the Lower Cretaceous Qingshuihe Formation (Tugulu Group) and the Upper Cretaceous Donggou Formation. Most of these grains show well-zoned crystal textures indicative of a magmatic origin. For all the seven samples, the dominant population (about 62.2%) in the age spectrum falls within 250–379 Ma, and most of the zircons are of magmatic origin according to their well-developed oscillatory zoning. Metamorphic zircons characterized by no zoning, faint zoning, or relatively typical fan-shaped zonation in CL images, only account for about 8.6%. Within the group 382–538 Ma, the magmatic zircon grains are also dominant (about 82.3%). However, the zircons ranging in the age interval 543–2852 Ma mainly display faint internal zoning, or inherited cores, interpreted to reflect a metamorphic genesis, and very few can be regarded as magmatic zircons. The few grains ranging in age from 207 to 249 Ma also seem to be of metamorphic origin due to their faint internal zoning. Except for two grains with very low values of 0.09 and 0.10, the Th/U ratios of the detrital zircons from the seven samples vary from 0.12 to 2.09, and are predominantly higher than 0.10, reflecting that magmatic zircons are in overwhelming majority.

**Cenozoic samples**

One hundred zircon crystals were randomly selected from each of the five samples collected in the Palaeogene (Anjinhaie Formation) to Quaternary (Xiyu Formation) section (Figs 3 and 4). Between 100 and 91 effective data points were obtained from these samples (Table 2). The U-Pb ages from the five samples range widely from 157 to 2856 Ma, and can be mainly divided into four groups: 157–197, 257–379, 381–532 and 620–2856 Ma (Fig. 5). Besides, there are also several individual ages comprised between 213 and 241 Ma (6 grains). The zircons ranging in age between 157 and 197 Ma mainly appear in samples from the Neogene Taxihe and Dushanzi formations, and almost all the grains show well-developed oscillatory zoning, indicative of a magmatic origin (see Appendix S2). The population of ages between 257 and 379 Ma is also the most important component in the age spectrum of every sample (Table 2 and Fig. 5), and the magmatic zircons are dominant (about 80%). Within the group between 381 and 532 Ma, the metamorphic zircons are largely in minority (about 14.9%), although the remaining crystals are all magmatic in origin (see Appendix S2). However, in the group of zircons dated between 620 and 2856 Ma, most grains are considered to be of metamorphic origin, based on their faint internal zoning or the occurrence of inherited cores. The six grains ranging from 213 to 241 Ma are all metamorphic zircons. Except for three grains with very low values of 0.02, 0.03 and 0.09, the Th/U ratios of detrital zircons of the five samples vary from 0.11 to 1.98, and are predominantly higher than 0.10, again indicating that overall many of those crystals are of magmatic origin although a non-negligible proportion are of metamorphic origin.

In summary, the U-Pb ages of detrital zircons from the 14 sediment samples ranging in deposition age from the latest Palaeozoic to the Quaternary, vary widely from 127 to 2856 Ma and can be mainly divided into four groups: 127–197, 250–379, 381–538 and 543–2856 Ma (Figs 5 and 6). Based on their morphological characteristics and internal texture, the genetic conditions of the various types of zircons have been determined. Magmatic zircons are dominant (about 78.9%), and metamorphic zircons are in minority (about 21.1%) (see Appendix S2).

The age population within 127–197 Ma with a sub-peak at 159 Ma (7.7% of the combined age spectra) is
This should be considered as volcanic debris associated further below. The age population within 250–379 Ma (a sub-peak of 318 Ma), accounting for 65.6% of the combined age spectra, is assigned to the late Palaeozoic magmatic belt of the NTS block and the northern margin of the Yili terrane (Fig. 1). These series can be regarded as the most important source of detrital materials through time. Finally, the age populations within 381–538 Ma (a sub-peak of 406 Ma) and 543–2856 Ma (a sub-peak of 912 Ma), accounting for 16.9% and 7.5% of the combined age spectra, may mainly and, respectively, reflect the early Palaeozoic magmatic rocks and Proterozoic basements in Central Tian Shan. Although now separated from the Junggar Basin by the North Tian Shan, these two sources also contributed to the sediment flux to the southern margin of the Junggar Basin.

DISCUSSION

Since latest Palaeozoic time, the provenance area of the sediments from the southern margin of the Junggar Basin has been mainly situated to the south in the Tian Shan area (Hendrix, 2000). This is consistent with the continuous northward component of the palaeocurrent directions. Even the Middle Jurassic to Lowermost Cretaceous growth of the Chepaizi-Mosuowan uplift, north of the section, seems to have had only a limited effect on the large-scale drainage system. Variations in zircon U–Pb age distribution within individual samples clearly indicate that sediment sources varied in relation with four distinct stages of the geological history of the southern Junggar Basin (Figs 6 and 7). These variations will be discussed below in chronological order to constrain the main stages of the topographic and tectonic evolution of the Tian Shan as determined by detrital U–Pb geochronology.

Late Carboniferous – Early Triassic phase

The U–Pb age pattern of the detrital zircons from the Aerasayi Formation (sample XJ09-092) is characterized by magmatic zircons with a single population peak age at 319 Ma (Fig. 5), indicating a single source of magmatic rocks. The associated conglomerates were investigated in the field to establish their occurrence, contact relationship and distribution within the Aerasayi Formation (Fig 8a). This should be considered as volcanic debris flow deposits (Xie, 1994; Di Crescenzo & Santo, 2005; Klubertanz et al., 2009) based on the occurrence of volcanic rocks in the volcanic-sedimentary sequences as well as the poorly sorted and sub-angular characteristics of the gravels in the conglomerate (Fig 8b). Moreover, the mottled pebbly coarse-grained sandstones represent autochthonous sedimentation (Di Crescenzo & Santo, 2005) which implies that the source was very close to the deposition area (Fig. 8a, b). Considering the single magmatic source and the proximal volcano-sedimentary context, we suggest that the real stratigraphic age of sample XJ09-092 is Late Carboniferous instead of Early Permian as previously indicated by the 1:200000 geological map of this area (BGMRXUAR, 1978, 1993, 2008). It implies a Late Carboniferous, rather than an Early Permian initiation of the Southern Junggar Basin. Field observations as well as published large-scale geological sections across the basin (e.g. Qiu et al., 2005, 2008) suggest that Late Carboniferous – Early Permian sedimentation occurred in an extensional setting with normal faults creating substantial topographical differences on localized structures (Fig. 7). The single provenance implies that during this period the late Palaeozoic magmatic belt in the North Tian Shan and the northern margin of the Yili terrane was the principal provenance area. The Late Carboniferous age of the Aerasayi Formation contradicts the model of formation of the Junggar Basin as a transtensional basin developing between the Tian Shan shear zones and the Irtyshev shear zone (Allen et al., 1994, 1995; Sengör and Natalin, 1996). Movements on those shear zones, and especially in the Tian Shan, have clearly been dated to the Permain (e.g. Wang et al., 2006; De Jong et al., 2009; Charvet et al., 2011). The evidences for extension suggest that the Junggar Basin was neither developing as a foreland basin (Carroll et al., 1992, 1995; Liu et al., 1994, 2000, Chen et al., 2001; Jia et al., 2003; He et al., 2004), but rather in a post collisional extensional setting (Fang et al., 2006a) or as a half-graben structure (e.g. Qiu et al., 2005, 2008). Wartes et al. (2002) suggested that the Permian extension could have been followed by contraction.
Due to the small amount of available zircon crystals in sample XJ10-009, the detrital U-Pb zircon age composition of the Upper Permian Wutonggou Formation (Fig. 5) is only indicative. However, both the Palaeozoic magmatic series of the NTS block and the Proterozoic basement of the CTS block contributed to the detrital material supply. This confirms that the CTS block was accreted to the NTS block at that time (e.g. Huang et al., 2010).

Fig. 7. Palaeogeographic reconstructions of key periods in the evolution of the Tian Shan – Junggar Basin history as described in the text. The map extends roughly between the Bayanbulak basin to the left and the Junggar Basin to the right. Only the major faults are shown such as the Main Tian Shan Shear Zone (MTSZ) or the Nikolaev line (see Jolivet et al., 2010). Question marks indicate possible but not documented movements on the faults. Faults in dotted lines are inactive. The arrow represents sediment provenance deduced from detrital U/Pb zircon ages and various sedimentology data described in the text. The topography was drawn using both provenance data and low thermochronology data obtained in the range by Dumitru et al. (2001) and Jolivet et al. (2010). Black arrows indicate major sources, dark-grey arrows indicate minor sources. Light-grey arrows indicate possible minor sources. The light-grey shaded areas indicate basins (deposition areas) and dark-grey shaded areas indicate lakes.
1980; Wang et al., 1990; Allen et al., 1992; Biske & Seltmann, 2010; Han et al., 2010; Charvet et al., 2011). It also shows that a limited amount of sediments supplied in the Junggar Basin were issued from the CTS implying a widening of the drainage system towards more distant sources. Erosion of the CTS and NTS blocks is consistent with the zircon (U-Th)/He and apatite fission track data obtained in the range which show a major exhumation episode during that period and thus the development of a strong topography (Dumitru et al., 2001; Jolivet et al., 2010). Finally, the large dextral strike-slip movements observed during the Permian along the main shear zones separating the CTS and NTS blocks confirm the strong tectonic activity during that time (e.g. Wang et al., 2006; De Jong et al., 2009; Charvet et al., 2011).

The Lower Triassic Shangcangfanggou Group sample (XJ09-094) shows some similarities with sample XJ09-092 from the Aerbasayi Formation (Fig. 5) with one major Carboniferous peak age. However, the slightly older peak age of 326 Ma in sample XJ09-094, associated to several minor middle to early Palaeozoic peaks that are only poorly recorded in sample XJ10-009, suggest exhumation of older, probably deeper sources. This exhumation may reflect active erosion during the Permian – Early Triassic in accordance with the low temperature thermochronology data obtained in the range (Dumitru et al., 2001; Jolivet et al., 2010). The Lower Triassic detrital material is interpreted as again mostly derived from the late Palaeozoic magmatic belt of the NTS block, whereas the minor Devonian to Ordovician ages reflect older magmatic series probably derived from the CTS block (Fig. 5). Those results suggest that, as in the Upper Permian (Wutonggou Formation), connections existed between the CTS block and the Junggar Basin (Fig. 7). Recycling of the Lower Permian sediments may also explain the occurrence of CTS-derived zircons but the age spectrum of those sediments is much larger, weakening that hypothesis.

Middle Triassic – Upper Jurassic phase

A first noticeable change in the distribution of detrital zircon U-Pb ages occurs in sample XJ10-011 from the Middle to Upper Triassic Xiaquangu Formation (Fig. 5) with the appearance of a distinct Ordovician peak age and of several Proterozoic to Archaean ages. Those last ages were already expressed in sample XJ10-009 from the Upper Permian Wutonggou Formation. However, they were only a minor proportion of an already extremely limited set of zircon ages. Furthermore, those ages completely disappear in the Lower Triassic XJ09-094 sample. Although some limited connections between the Junggar Basin and the Precambrian basement of the CTS block existed during the Upper Permian and the Lower Triassic, this connection appears clearly established in the Upper Triassic. The provenance in sample XJ10-011 is thus interpreted as a mixture of three sources: the late Palaeozoic magmatic belt in the North Tian Shan and the northern margin of the Yili terrane representing the major zircon population (peak age of 327 Ma), the early Palaeozoic magmatic rocks in CTS representing the second major population (peak age of 450 Ma), and finally a significant contribution from the Precambrian basement of the CTS block (Fig. 5). Recycling of the upper Palaeozoic – lower Mesozoic series could also partially explain apparent increase in Precambrian and early Palaeozoic ages.

Fig. 8. (a) Volcanic-sedimentary sequences of the Aerbasayi Formation; (b) Characteristic gravels from conglomerates of the volcanic-sedimentary sequences; (c) Typical red gravels and pebbles of the Late Jurassic Qigu Formation (white circles) and brown-reddish conglomerate pebbles of the Kalazha Formation found in the Dushanzi Formation conglomerate (black circles); (d) Late Jurassic tuffaceous sandstone pebbles found in the Dushanzi Formation conglomerate (white circles).

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However, the age spectra, and especially the dominant Palaeozoic peak cannot be solely attributed to recycling. The increased contribution from the CTS block implies a noticeable evolution of the drainage system and thus of the regional topography. The NTS source being important, positive reliefs were certainly still present in that area. However, this topography was probably smooth enough to allow rivers to cut through and bring material from the CTS block to the south. Sediment transport was then occurring over large distances and clastic sedimentation migrated southwards covering surfaces previously in erosion. The major topographic barrier formed by the NTS block since the Early Permian was no more present. This is consistent with the progressive erosion of the topography that resulted from the Permian accretion events as seen by the low temperature data in the range (Dumitru et al., 2001; Jolivet et al., 2010). The extensional setting that was prevailing in the Junggar Basin during the Late Carboniferous – Permian probably ended in the Lower Triassic allowing a progressive decrease of the locally strong topography induced by normal faulting. From Middle Triassic, tectonic subsidence ceased and the southern Junggar Basin clearly became slowly a subsiding basin. We have no real argument to discuss the origin of this subsidence, but it could be due to relaxation of far-field constrains generated by the Permian accretion events.

The provenance of the Lower Jurassic Baodaowan Formation (sample XJ09-097) (Fig. 5) mainly includes the late Palaeozoic magmatic belt of the NTS block (peak age of 300 Ma) and the early Palaeozoic magmatic rocks of the CTS block (peak age of 465 Ma). Proterozoic ages are nearly absent. The observed unconformity between the Upper Triassic and Lower Jurassic indicates limited vertical tectonic movements and a possible slight reorganization of the drainage pattern. We do not have enough information to fully discuss those changes. However, Dumitru et al. (2001) suggested that the Permian – Triassic exhumation phase had been overprinted by a subsequent Early Jurassic cooling phase. Jolivet et al. (2010) related that episode to the collisions of the Cimmerian blocks to the south (e.g. Jolivet et al., 2001; Roger et al., 2010, 2011). Nonetheless, the widespread Lower and Middle Jurassic series, including the well-developed coal strata and the concentration of thick coal seams in the Middle Jurassic Xishanyao Formation, attest the widening of a passively subsiding Junggar Basin (Figs 3 and 4). Fang et al. (2005) suggested that the southern edge of the basin extended at least to the south of the Houxia area (Fig. 1).

The age spectrum of the Middle Jurassic Toutunhe Formation (sample XJ10-018) presents a dramatic change, with the first appearance of zircons from sub-contemporaneous Mesozoic magmatic sources (peak age of 168 Ma) (Fig. 5). In addition to the occurrence of those zircons of clear magmatic origin, several lines of evidence suggest that magmatism, limited in volume, but distributed over a wide area occurred in Central Asia during the Mesozoic (see discussion below). The other two sources of zircons in sample XJ10-018 again correspond to the late Palaeozoic magmatic belt of the NTS block (peak age of 329 Ma) and to the early Palaeozoic magmatic rocks of the CTS block (peak at 520 Ma) (Fig. 7). The Toutunhe Formation also marks the end of the long-lasting general retrogradation phase that initiated in the Late Carboniferous and ended with the lacustrine facies of the Middle Jurassic Xishanyao Formation. Although retrogradation was consistent with a progressive erosion of the topography during the late Palaeozoic – early Mesozoic, and the coeval widening of the drainage pattern and of the sedimentation area, the onset of a progradation phase suggests topographical or climatic changes. We have only a limited amount of data to discuss this issue, but the suspected tectonic reactivation of the range that initiated during the Lower Jurassic (see above) could be an explanation for this change between retrogradation and progradation.

The Upper Jurassic Qigu Formation (sample XJ10-100) is very similar to the Middle Jurassic sample XJ10-018. The peak age of 159 Ma again reflects the products of coeval Late Jurassic volcanic activities. The peak age of 300 Ma represents sediments derived from the NTS magmatic belt. The older ages may be either derived from the CTS block or from recycling of the Mesozoic cover deposited on the NTS basement.

**Lower Cretaceous – Paleogene phase**

The sharp facies variation from the alluvial fan of the Kalazha Formation to the lacustrine deposits of the Lower Tugulu Group marks the end of the Middle to Upper Jurassic progradation phase and the onset of a new progradation. The age population pattern of the Lower Cretaceous Tugulu Group (sample XJ10-016) (Fig. 5) still yields Jurassic volcanic zircons attesting for recycling from the underlying sedimentary series. The proportion of the age population with a peak of 297 Ma rose markedly to become predominant (65.0%), suggesting that the contribution of the late Palaeozoic NTS magmatic belt further increased as a source. This, associated to the potential recycling of the Jurassic series may indicate renewed erosion of the NTS block. During the Early Cretaceous, the southern margin of the Junggar Basin was thus under erosion. The surface of the basin decreased and its southern boundary shifted northwards significantly, near the present-day southern Junggar Basin boundary (Fang et al., 2006a).

However, the proportion of the NTS late Palaeozoic source decreases to 48.5% in the age populations of the following Upper Cretaceous Donggou Formation (sample XJ10-015) (Fig. 5). The peak age of 143 Ma recorded in that sample by magmatic zircons indicates the occurrence of Late Jurassic – Early Cretaceous (up to 127 Ma) magmatism in the region. The decrease in proportion of the late Palaeozoic source (peak age of 312 Ma) can be explained by an increased amount of sediment recycling...
from the underlying upper Palaeozoic – lower Mesozoic sequence. Material eroded from the NTS late Palaeozoic magmatic belt are simply diluted within the recycled zircons of various origin. The early Palaeozoic age peak of 434 Ma also suggests that either the connections with the CTS block still exist or that, more probably, sediment recycling occurs. Although the reactivation of the topography observed during the Lower Jurassic seems to have had no impact on the Junggar Basin (continued widening and possibly reinforced subsidence), the Cretaceous period is clearly marked by inversion of the southern margin of the basin (Fig. 7). The geodynamic mechanism that induced this basin inversion remains to be constrained and several hypotheses have been put forward such as the collision of the Lhasa block to the south (Hendrix et al., 1992; Gu, 1996; Fang et al., 2006b). However, except for the occurrence of the Jurassic magmatic sources, the Early Cretaceous detrital zircon ages pattern remains similar to the overall Mesozoic series pattern, and we infer that the modifications in the basin-range relations was a relatively minor internal adjustment compared to the previous estimates. This is consistent with the long period of tectonic quiescence recorded by fission track thermochronology studies in Tian Shan, Mongolia and Northern Tibet during the Cretaceous (Jolivet et al., 2001; Jolivet et al., 2007; Vassallo et al., 2007; Roger et al., 2010). The basic properties and essential characteristics of the basin were preserved.

The age patterns of the two Palaeogene samples (XJ09-010 and XJ09-011) are quite similar. The Mesozoic ages have disappeared and the late Palaeozoic source now largely dominates. Although the late Palaeozoic age peaks of 313 Ma are identical to the peak age of 312 Ma of sample XJ10-015, the disappearance of the Mesozoic magmatic zircons clearly excludes direct sediment recycling from the Cretaceous and Jurassic series. For sample XJ09-010 from the Anjihai Formation, the peak ages of 313 Ma and 445 Ma approximately correspond to the magmatic events in the Late Carboniferous and Late Ordovician. These, respectively, correspond to the late Palaeozoic magmatic belt and the Late Ordovician granites, which are two important sources widespread in Central Tian Shan. The Precambrian ages reflect the contribution of older basement from the CTS block although they may also be partially recycled from pre-Jurassic Mesozoic series. The Junggar Basin remained in an overall relatively stable basin-range setting during that period (Fang et al., 2004; Jolivet et al., 2010). However, later in the palaeogene, uplift probably initiated leading to progressive modifications of the drainage pattern and to the decrease of the contribution from CTS block sources (especially in the Shawan Formation) and the increased erosion of the sedimentary series now reaching down to pre-Jurassic strata (Fig. 5).

In summary, the Middle–Late Triassic to Palaeogene basin-range pattern was overall characterized by a large source area and a relatively low topography that was punctually high enough to generate coarse clastic sediments, but not enough to create long–lasting topographic barriers for the sediment supply. This setting is consistent with a postextensional thermally subsiding basin associated to a palaeo-range which has been progressively eroded away without much tectonic activity (Dumitru et al., 2001; Vassallo et al., 2007; Jolivet et al., 2007, 2010; Glorie et al., 2010). Two relatively minor internal adjustments occurred in the Lower Jurassic and in the Earliest Cretaceous probably in relation with the various accretion episodes that occurred along the southern margin of Asia during the Mesozoic.

**Neogene to Quaternary phase**

From the Neogene Taxihe Formation (samples XJ09-003 and XJ09-017), a relatively important change took place again in the distribution of detrital zircon U-Pb ages reflecting, a new transformation in the source system (Fig. 7). In those samples the Jurassic magmatic source, characterized by the peak ages of 162 and 168 Ma is again present (Fig. 5). Recycling of the Mesozoic series is further attested by the lithology of the pebbles within the Dushanzi Formation. For example, the red gravels of the Late Jurassic Qigu Formation and the brown-reddish conglomerates of the Kalazha Formation (Fig. 8c), as well as the Late Jurassic tuffaceous sandstone pebbles (Fig. 8d) are all found in the Dushanzi Formation conglomerates. The zircons from the late Palaeozoic NTS magmatic belt are again the major components and are derived both from contemporaneous erosion of the NTS basement and sediment recycling (Fig. 5). However, the proportion of zircons derived from the early Palaeozoic magmatic rocks (age peaks of 402 and 406 Ma) and the Proterozoic basement of the CTS block obviously increases. Connections between the internal parts of the growing range and the Junggar Basin are unlikely (the topographical barrier formed by the uplift of the NTS was probably already important), and those zircons are most probably recycled from the Mesozoic strata.

The distribution of detrital zircon U-Pb ages in the Quaternary Xiyu Formation (sample XJ09-021) basically retained the characteristics of the Neogene samples XJ09-003 and XJ09-017, indicating similar provenances. The main difference is that during deposition of the Xiyu Formation, the contribution from the Mesozoic magmatism decreased significantly (3.0%), whereas the older Central Tian Shan basement components were more represented (13.1%). This can be explained by erosion of progressively older cover series. Today, the whole Late Carboniferous to Quaternary series of the northern piedmont are being eroded and recycled. During the Neogene to Quaternary period, the southern margin of the Junggar Basin became a piedmont and the basin a true foreland basin.

**Notes on the Mesozoic volcanism**

There are relatively few direct field evidences of Mesozoic magmatic activity in the southern margin area of the
Junggar Basin. However, near the Manas River and slightly further east, thin tuffaceous sandstone intercalations have been reported in the Lower part of the Qigu Formation (BGMRXUAR, 1978, 1993, 2008). In addition, numerous studies indicated that Mesozoic volcanism was extensively distributed both in northern Xinjiang and in the surrounding regions (Hān et al., 1999; Sobel & Arnaud, 2000; Ji et al., 2006; Jolivet et al., 2007; Xu et al., 2008; Guo et al., 2010). For example, a whole rock 40Ar/39Ar age of 192 Ma has been obtained on a basalt flow from the Karamay region in western Junggar (Xu et al., 2008). Similar ages were reported on volcanoes in the nearby Gobi Altay, Mongolia (Jolivet et al., 2007). In NE Tibet, several layers of volcanic rocks are interbedded in the sequences of Middle Jurassic continental clastic rocks of the Tuoge, Duobagou and Lucaogou area of the Dunhuang basin (Zhang et al., 1998).

Volcanism is not restricted to the Jurassic and ages of 100 and 70 Ma have been obtained on olivine basalts and basalts from the Tuyon basin, southwest Tian Shan (Ji et al., 2006; Wang et al., 2000b). In North Tibet, Early Cretaceous basaltic magmatic activities are reported in the Sanweishan area (Feng et al., 2010). In the Hanxia and Hongliuxia area of the Jiuxi basin, Lower Cretaceous volcanic intercalations and two phases of magmatism were identified at 112–106 and 83 Ma respectively (Yang et al., 2001; Wang et al., 2004).

Potential sources of this intracontinental volcanism are still elusive. Although it is beyond the scope of this article to solve this issue, we note nonetheless that in Tian Shan this magmatism occurred slightly after the Lower Jurassic renewed exhumation phase observed in the range (Dumitru et al., 2001; Jolivet et al., 2011) and before the Lower Cretaceous inversion of the southern Junggar Basin. This might suggest that magmatic activity took place during an apparently tectonically quiet period.

CONCLUSIONS

The detrital zircon geochronology and related genetic mineralogy studies show that the detrital zircons from the 14 samples of the latest Palaeozoic to Quaternary formations are mostly magmatic in origin, with some minor input from metamorphic sources. The U–Pb detrital zircon ages range widely from 127 to 2856 Ma and can be divided into four main groups: 127–197 (sub-peak at 139 Ma), 250–379 (sub-peak at 318 Ma), 381–538 (sub-peak at 406 Ma) and 543–2856 Ma (sub-peak at 912 Ma). These groups, together with the available measurements of palaeocurrent directions indicate that the detrital zircons (and thus probably most of the sediments) were largely derived from the Tian Shan area to the south since the basin initiated in Late Carboniferous time. The 250–379 Ma age group, accounting for 65.6% of the combined age spectra, is assigned to the late Palaeozoic magmatic belt in the North Tian Shan and the northern margin of the Yili terrane, which can be regarded as the most important source of detrital material through times. The 381–538 and 543–2856 Ma age groups, accounting, respectively, for 16.9% and 7.5%, of the combined age spectra mainly reflect the early Palaeozoic magmatic rocks and Proterozoic basement of Central Tian Shan. Finally, the 127–197 Ma age group, representing 7.7% of all ages, corresponds to Mesozoic volcanism (mainly tuffs). The occurrence of these Jurassic volcanic zircons within the Neogene sediments highlights the importance of sediment recycling within the evolving Piedmont. That recycling, however, is not restricted to the Tertiary and occurred regularly throughout the Mesozoic history of the range, especially during the Cretaceous.

The provenance and basin-range pattern evolution of the southern margin of the Junggar Basin can be generally divided into four stages as follows. (1) During the Late Carboniferous to Early Triassic, the provenance is relatively unimodal. The detrital material was almost exclusively derived from the late Palaeozoic magmatic belt of the North Tian Shan and the northern margin of the Yili terrane. Only a small amount of sediment was derived from the Central Tian Shan. This is interpreted in terms of near-source sedimentation in basin developing in a post-orogenic extensional setting or as a half-graben. Strong topography in the range is suspected. (2) A major change in the history of the Junggar Basin occurred during the Middle–Late Triassic. Until the Upper Jurassic, the southern Junggar Basin progressively extended towards the south reaching beyond the Houxia area and evolved as a passively subsiding basin. The topography resulting from the late Palaeozoic–early Mesozoic tectonic movements was progressively eroded and the drainage system reached the CTS block. (3) The following noticeable event corresponds to the Lower Cretaceous–Palaeogene inversion of the southern Junggar Basin illustrated by the onset of erosion of the Jurassic sedimentary series and the progressive northward migration of the edge of the basin. However, it seems that although effective, this event remained of limited magnitude and that no major topography developed in the range. (4) Finally, major Neogene reactivation of the Tian Shan led to the development of a piedmont along the northern edge of the NTS block and the Junggar Basin became a true foreland basin. The increasing amount and diversity of early Palaeozoic and Precambrian zircons recalls the strong recycling of sediments from the entire Mesozoic and Tertiary sedimentary sequences of the North Tian Shan Piedmont.

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Appendix S1: U-Pb Geochronologic Analysis of Detrital Zircons from the 14 Sandstone Samples.

Appendix S2: Representative CL Images of Zircons from the 14 Sandstone Samples. White Circles Show the Location of U-Pb Analysis. Numbers are U-Pb Ages in Ma.

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REFERENCES


Source to sink relations between the Tian Shan and Junggar Basin.


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