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Reappraisal of the Jianchuan (SE Tibet) Cenozoic basin stratigraphy and structural implications.

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Keypoint

Sediments of the Jianchuan basin, SE Tibetan plateau, have a late Eocene age.

Keywords

SE Tibetan plateau, Jianchuan basin, Stratigraphy, Late Eocene, U/Pb dating

Abstract.

We present a new stratigraphy of the Jianchuan basin, one of the largest Cenozoic sedimentary basins in southeastern Tibet. This basin was thought to record sedimentation from the Eocene to the Pliocene, and as such was the focus of several studies aiming at constraining the environmental, tectonic and topographic evolution of the area. Within the Shuanghe and Jianchuan formations thirteen new zircon U/Pb ages and one biotite ⁴⁰Ar/³⁹Ar age of interbedded and crosscutting high K magmatic rocks show that a brief magmatic event occurred at ~35.22 ± 0.30 Ma. The uppermost formation (Jianchuan), supposedly Pliocene in age, belongs to this magmatic event. All sedimentary formations are thus Eocene in age; with neither Oligocene nor Miocene sediments. The coal-bearing Shuanghe Formation yielded a large amynodontid typical of the Late Eocene Ergilian interval (37.2 to 33.9 Ma).
Sedimentation of the Shuanghe Formation took place in a short time interval at ~35.88 ± 0.35 Ma, after a large-scale drainage reorganization that induced the abandonment of a large braided river system (Baoxiangsi formation). This reorganization was possibly linked with the initiation of the left-lateral Ailao-Shan Red River fault and/or to widespread magmatism in the Jianchuan basin. Previous high paleoaltitude estimates for the Jianchuan basin are re-evaluated and yield a value of 1200+/-1200 m in the late Eocene. High K magmatism emplaced at the time of E-W shortening in a zone of ~200 km of diameter, which was later cut and left-laterally offset ~600 km by the Ailao-Shan Red River shear zone.

Introduction

Tibet is the widest and highest plateau on Earth. It covers 200 000 km$^2$ at a mean elevation of 5000 m. The formation of this high elevation landscape is considered to be linked with the convergence between the Indian and Eurasian plates and their continental collision that started ~55 Ma ago. Debates on how the convergence is absorbed and the timing and geodynamic processes of the plateau uplift are still vivid. Various models have been proposed, such as homogeneous thickening [England et Houseman, 1986; Murphy et al., 1997], mantle delamination [Harrisson et al., 1992], Indian plate underthrusting beneath the Asian plate [Powell et Conaghan, 1973], lateral extrusion of continental blocks along major strike-slip faults [Tapponnier et al., 1982; Tapponnier et al., 2001], and channel flow [Royden et al., 1997; Clark and Royden, 2000].

One key observation that would help to test the various models is the temporal evolution of the deformation and altitude at the plateau margins. In particular, all mechanisms mentioned above have been proposed to take place in SE Tibet. In that zone, the Jianchuan Cenozoic basin has been the focus of several studies as it is a wide basin, which, according to geological maps, records continuous sedimentation from the Eocene to the Pliocene. As such it may contain sedimentary archives allowing following the paleoenvironmental evolutions of the area since the onset of the collision, as well as altitudinal and latitudinal variations.

However, dating continental sediments is difficult and, whilst these contain volcanodetritic levels and are crosscut by plutonic rocks, no systematic study was previously conducted to provide the absolute ages of the sedimentary formations. These ages could then be used to constrain the tectonic and altitudinal variations through time. We performed geological mapping and geochronologic dating. This allows us to propose a new stratigraphy and to
constrain the absolute timing of sedimentation, which has fundamental bearings on the previous studies conducted in the Jianchuan basin and on the tectonic evolution of eastern Tibet.

1. Geological Setting

The Yunnan highlands stand at ~2000 m a.s.l. between the South China sea and the ≥4000 m a.s.l. southeastern Tibetan plateau (Figure 1a). The area results from the amalgamation of continental blocks through the Paleozoic and Mesozoic with the Qiangtang and Songpan-Garze blocks to the North, and the Indochina and South China blocks to the South. The Jianchuan Cenozoic basin is located in the southernmost part of the Qiangtang block, lying east of the N-S Benzilan suture, part of the Jinsha suture zone [e.g., Leloup et al., 1995; Roger et al., 2003]. The last suturing event dates back to the Lower Triassic (Indosinian orogeny) and the Upper Triassic sediments mark a major angular unconformity [e.g., Roger et al., 2003; Faure et al., 2014]. The Mesozoic corresponds to widespread continental sedimentation from the Triassic to the Eocene (“red beds”).

The Jianchuan basin is ~30-km-wide (E-W) and ~100 km long (N-S) [BRGMRYP, 1990] (Figure 1b). It is one of the largest Cenozoic basins in SE Tibet and Yunnan and has a triangular shape bounded to the west by the Qiaohou thrust belt and to the east by the Jianchuan fault (Figure 1b, Figure 2, SM 1). The Cenozoic sediments now stand at elevations between 2300 to 3500 m where sedimentation is limited and erosion prevails. Present day sedimentation takes places in the hanging walls of the Qiaohou and Jianchuan active faults that both show a normal component of motion. The Qiaohou fault is part of the Red River fault system and is predominantly right-lateral [e.g.; Leloup et al., 1995; Replumaz et al., 2001]. The Jianchuan fault belongs to the active Lijiang pull-apart basin (Figure 1b), and is predominantly normal with a left-lateral component [e.g.; Leloup et al., 1995] with the Jianchuan city standing in the Dianwei basin, where present-day sedimentation takes place (Figure 2).

Whilst standing east of the India/Asia collision front, the area was affected by intense post-Eocene deformation with folds and major strike-slip faults. The folds trend mostly ~N-S and reflect a ~E-W compression [e.g.; Leloup et al., 1995]. During the Miocene, such compression was coeval with left-lateral strike-slip motion along the ~900 km long Ailao Shan-Red River (ASRR) shear zone standing along the present-day Red River fault system.
(Figure 1a). Total left-lateral motion amounts to $700 \pm 200$ km [e.g.; Leloup et al., 1995, 2007; Faure et al., 2014]. The initiation age of the left-lateral motion is still debated and ranges from 28 to 36 Ma [e.g., Cao et al., 2011, Leloup et al., 2007; Zhang and Schärer, 1999; Gilley et al., 2003; Palin et al., 2013]. The end of motion took place probably at $16 \pm 1$ Ma [e.g. Leloup et al., 2001]. Reactivation of the fault zone in the opposite sense (right-lateral) took place after 11 to 5 Ma for a $\sim 60$ km offset [e.g.; Leloup et al., 1995; Replumaz et al., 2001].

An Eocene-Oligocene ultrapotassic magmatic episode occurred throughout Yunnan [Schärer et al., 1994, Chung et al., 1998, Wang et al., 2001, Liang et al., 2007, Lu et al., 2012], in eastern and central Tibet and in the Qiangtang block [review of Chung et al., 2005]. Some of these rocks are found deformed within the ASRR and define a $\sim 600$ km left-lateral offset [e.g., Leloup et al., 2001] as similar rocks are found in northern Vietnam, south of the fault [e.g., Zhang and Schärer, 1999; Liang et al., 2007] (Figure 1a). These widespread ultrapotassic rocks have been interpreted as products of continental subduction [Wang et al., 2001, Ding et al., 2003], thetysian slab break-off [Kohn and Parkinson, 2002], or lithospheric delamination [Chung et al., 1998, 2005, Lu et al., 2012]. In Yunnan, the emplacement age of the plutonic intrusions and volcanites range between $\sim 33$ and $\sim 37$ Ma (Table SM 2).

2. Stratigraphy of the Jianchuan Cenozoic basin

2.1 Conventional stratigraphy

On small-scale geological maps, the Jianchuan basin sediments are attributed to Eocene to Neogene [i.e., Pan et al., 2004; BGMRYP, 1990]. This is consistent with larger-scale maps and previous papers where five main formations are distinguished in the Jianchuan basin, whilst detailed mapping vary [Yunnan Geological Survey, 2008; Yan et al., 2012; Yang et al., 2014; Wei et al, 2016; Tong et al., 2015]. From bottom to top these are the Yunlong, Guolang, Baoxiangsi, Jinsichang, and Shuanghe formations (Fm) (Figure 3; Table SM 3).

The Yunlong (E$_1$ or Ey) and Guolang (E$_2$ or Eg) Fms. are described as purple–red siltstones, mudstones and sandstones with intercalations of massive conglomerates. Total thickness ranges from 800 to 2800 m. The Yunlong Fm is described as also containing gypsum layers (Table SM 3). However, these two formations are sometimes considered as a single one, called Mengyejing Fm (E1m) [Yunnan Geological Survey, 2008; BGMRYP,
1996] or Gaolacun Fm (E2) [BGMRYP, 1990]. The Baoxiangsi Fm (E2 or Eb) corresponds to massive sandstones showing parallel- and cross-bedding with some conglomeratic and breccia levels at the base. The Baoxiangsi Fm total thickness is ~800 m (Table SM 3).

The Yunlong Fm contains a typical Paleocene charophyte flora, such as Obtusochara lanpingensis, Obtusochara elliptica, Tectochara subelongata, and Gyrogona qianjiangica [BGMRYP, 1996]. Paleocene to early Eocene ostracods are present in both the Yunlong and Guolang Fm, including Limnocythere yunlongensis, Limnocythere spinosalata, Sinocypris excelsa [BGMRYP, 1996] as well as Eucypris and Candonina [YBNGR, 1974, 1984], together with conchostracans, and charophytes [BGMRYP, 1996]. The Baoxiangsi Fm contains charophyte assemblages and late Eocene mammalian faunas, such as Eoentelodon likiangensis, Lunania cf. youngi, and Honanodon hebetis [BGMRYP, 1996]. This led to attribute a Paleocene age to the Yunlong and Guolang Fms and an Eocene age to the Baoxiangshi Fm. Zircon U–Pb dating from a trachydacite, interpreted as a lava flow overlying the Yunlong Fm (sample DX030-6, 36.59 ± 0.57 Ma, Figure 2), was considered as evidence that the overlying formations are upper Eocene or younger in age in good accordance with the previously proposed ages [Yang et al., 2014]

The Jinsichang Fm (E2js) is a very thick (> 2600m) series of sandstones and conglomerates (Figure 3; Table SM 3). It contains Oligocene plant fossils, such as Myrica cf. angustifolia, and Taxodiaceae inde. [BGMRYP, 1996], and ostracod assemblages [BGMRYP, 1990].

The Shuanghe Fm (N1s) consists of mudrock and coal beds interstratified with sandstones, and includes occurrences of volcanoclastic sediments (Figure 3; Table SM 3). Its age is constrained to be Miocene by a variety of fossil plants, bivalves, gastropods, and ostracods [BGMRYP, 1996].

The Jianchuan Fm (N2j) corresponds to volcanic, volcanosedimentary and pyroclastic rocks for which a Pliocene age (2.4–3.1 Ma) has been proposed, based on apatite fission track (AFT) ages [Xiang et al., 2009] (Figure 3; Table SM 3).

2.2 New stratigraphy

Whilst the stratigraphy of the Jianchuan basin could appear firmly established and has been extensively used in other studies, our own field observations and new geochronologic ages yield a different chronology and palaeoenvironmental interpretation. The major
The difference is that only one upper Eocene volcano-plutonic episode affected the area. As a consequence, the whole basin must have deposited prior to the Oligocene. We thus propose a new stratigraphic column, structural map and geological cross sections of the Jianchuan basin (Figure 2; Figure 3; Table SM 3). As the main characteristics of the formations stay valid we kept some of the old designations but clarify below their extent, relationships and depositional (environmental) settings. The absolute age constraints are discussed thereafter in Section 3.

No gypsum interbedded with red siltstones was found in the Jianchuan basin. We thus consider that the purple-red sandstones, siltstones and mudstones that outcrop at the base of the basin belong to the Mengyanjing Fm (E1m) as defined by BGMRYP [1990] for the Zhongdian -Lijiang subregion encompassing the Jianchuan basin. This formation was referred to as the Guolang (E1g) or Denghei (E2d) formations in previous studies (Table SM 3). The Mengyanjing (E1m) Fm consists of red siltstones, with occurrence of local conglomerate levels. Some outcrops show root traces, bioturbation evidence and thin carbonate levels (Figure 4a). Channel-fill conglomerates and metric carbonates levels are locally found interbedded within red siltstones, particularly in the northeastern part of the basin, where the series locally onlap on a paleorelief carved in Paleozoic Shigu metamorphic schists (Figure 5). These sediments are consistent with a deposition in a flood-plain (i.e. low energy) environment with local occurrences of alluvial-fan debris-flow deposits. The precise relationship of the lower part of the Mengyanjing Fm with the top of the Cretaceous sequence has not been observed. Red siltstones are cut by numerous metric to decametric lamprophyres sills surrounded by centimeter-scale contact aureoles. Locally the formation is folded with bed dips ≥ 70°.

The Baoxiangsi Fm (E2b) consists of massive, well-sorted, multi-storey channel-fill fluvial sandstones that produce large cliffs and spectacular erosion features at several locations (Shibaoshan in the south and Liming in the north for instance). In many places beds are nearly horizontal and concordant with the underlying Mengyanjing Fm. However, along the northern margin of the basin the Baoxiangsi Fm rests on the Shigu metamorphic schists over a basal conglomerate [Studnicki-Gizbert, 2006]. Wei et al., [2016] advocate for an angular unconformity between the base of the Baoxiangsi Fm and the top of the Mengyanjing Fm, but we did not find direct evidence for it. Massive sandstone levels are locally eroded by meter-thick conglomerates corresponding to channel-fill geometries. Conglomerates include rounded centimeter to decimeter-scale boulders, mainly composed of Triassic carbonates and
without volcanic rocks. Few dykes have been mapped as crosscutting the sandstones. The sandstone levels locally contain vegetation remains. Sandstone colors vary from orange to yellowish. Centimeter-scale mud balls were often observed at the base of channel fills. Bed thickness ranges between 50 cm and a few meters. Sandstone bodies mostly rely on stacked-fluvial bars, themselves formed from compound cross-bedded units. The occurrence of downstream accreting barforms and channel-fills deposits with a low range of foreset dip azimuths (most often dipping east-southeast), the abundance of planar cross-bedding and the presence of mid-channel longitudinal bars is characteristic of braided-fluvial systems [e.g., Best et al., 2003] (Figure 4b, c, d). Given the presence of conglomerate levels, the braided-river system was proximal to a local relief, in particular to the northeast basin-margin from which lateral sources likely originate. Outcrops of the Baoxiangsi Fm extend for ~100km in a NW-SE direction all the way across the Jianchuan basin. Some outcrops have been reported SE of the Jianchuan basin resting directly on top of Paleozoic rocks. Regional maps also reports the occurrence of similar sediments ~40km east, immediately East of the Quaternary Lijiang-Heqing basin (Figure 1a).

The Shuanghe Fm (E2s) is usually described as resting unconformably on all underlying units. However it is never found on top of the Baoxiangsi Fm but rather aside, and appears conformable to the Mengyanjing Fm. The base of the formation corresponds to a multi-storey carbonate level that we designate as the Jiuziyan Fm (E2jz). In particular, at site S254 (Figure 2) a quarry shows a ~30-40m-thick level of carbonates that consist of green partially carbonated claystones and carbonate-fill channels. The carbonates contain peloids, fossils reeds andstromatolites, most of them in life position. The claystones matrix often contains poorly sorted gravels (0.5 to 1.5 cm), some of them being of magmatic origin, and centimetric boulders. The base of the Jiuziyan Fm locally corresponds to carbonate conglomerates with channel-fill geometries (i.e at site S607, Figure 4f, g). This erosive base suggests a sedimentation gap between the top of the Mengyanjing Fm and the bottom of the Jiuziyan Fm whilst the two formations appear conformable. The upper part of the Jiuziyan Fm is locally capped by few meter-thick green sandstones. The Jiuziyan Fm appears to be restricted to a ~15x10 km area in the NE of the Jianchuan basin. Other outcrops of limestones are located outside of the Jianchuan basin close to the Yangtze river first bend (S862, Figure 2). There, a >110m-thick series of pale recrystallized limestones including bio-constructions, lies horizontally above a ~2m thick conglomeratic level. These sediments are unconformable
on top of green schists (Shigu schists) dipping ~40° to the west. These limestones possibly belong to the Jiuziyan Fm but their exact extent and age are still unknown.

The Shuanghe Fm (E2s) resting on top of the Jiuziyan Fm consists of poorly consolidated yellow sandstones, intercalated with rare centimetric-scale lacustrine carbonate layers. The sandstones are regularly interbedded with coal deposits and occasional lava flows (Figure 6a), tuff and volcano-sedimentary levels. The Shuanghe Fm is cut by intrusive rocks, mostly lamprophyres, forming numerous sills in the coal levels (Figure 6d). The formation may have had a much wider extent, since it is found in the deformed slice along the Qiaohou Fault (i.e S222, Figure 2).

At site S272 (Figure 2), along the road between Jianchuan and Lanping, the base of the Jinsichang formation (E2js) monoclinally dips to the NNW and directly rests on E1m siltites that are affected by folds with NE-SW axis. Cartographically the conglomerates also rest on top of the E2b Fm, especially in the northern part of the basin, but we could not confirm this relationship. Boulders are mostly composed of Triassic sandstones but at one location (S556) the clasts also contain syenite. On some maps, the Jinsichang formation extends to the northeastern part of the Jianchuan basin. However, field investigation showed that red conglomerates in that area are found within E1m below E2jz limestones. The Jinsichang formation was thus probably deposited in medium to distal alluvial fans, most likely originating laterally, from the western margin of the main basin axis.

Between sites S254 and S805, the Shuanghe formation is affected by an anticline with a wavelength of a few km and an axis trending NNW-SSE (Figure 7b). The Jianchuan formation (E2Jc) appears to dip monoclinally to the east above this fold and it has been interpreted to correspond to a Neogene volcanodetritic event. However our observations suggest that the Jianchuan formation directly originates from the Shamao Shan Syenite complex and that it is not Neogene but Eocene in age (see below).

On top of the southern outcrops of the E2s Fm we found distinctive quartz-rich conglomerates and conglomerates with gypsum that where not previously described. It is not clear if these conglomerates are lateral equivalent of the E2js, or more probably correspond to much more recent (Neogene ?) deposits that we ascribe to the Sanying Fm (N2S) (see below) but without many evidence.
Quaternary basins develop in the hanging wall at the foot of the Jianchuan fault. In the southern part of the Dianwei basin outcrop yellow-white lithic sandstones and mudstones interbedded with purple mudstone and lignite (i.e. S633). Most maps allocate this outcrop to the Shuanghe Fm because it contains coal deposits. However the legend of the Jianchuan 1 / 200 000 geological map reports the occurrence of a distinctive Pliocene Sanying Fm (N2S) corresponding to that description, and we thus ascribe these deposits to that particular formation. At the regional scale the Pliocene and Quaternary formations are often found in the hanging wall of active faults.

3. Absolute age constraints

As emphasized in sections 1 and 2, the Jianchuan area is rich in magmatic bodies and volcanosedimentary rocks that can be dated using geochronological techniques. In order to constrain the age of some of the formations and help to assess the various proposed stratigraphic columns, we compiled available geochronological ages and conducted in situ U-Pb dating on zircons from thirteen samples (Figure 2, Table 1). We also dated biotites from a sample with the 40Ar/39Ar method. Moreover, the analysis of paleontological remains within the Shuanghe Fm gives important time constraints.

3.1. Geochronologic constraints

An important prerequisite for the interpretation of geochronologic ages is to determine the precise nature of the dated rocks. If they are interstratified (effusive or volcanosedimentary) their age will give a minimum age for the layers they overlay, while if they are intrusive, their emplacement age will give a maximum age for the layers they cut. Nine samples correspond to lava flows or volcano-sedimentary sediments interbedded within the series, and four samples are intrusive rocks (sill, dyke and neck). Ages from the literature correspond both to intrusive and interstratified rocks (see SM 2 for details).

3.1.1. New geochronologic data.

Most samples were crushed and zircon grains separated at the Laboratoire de Géologie de Lyon, France, using standard magnetic and density techniques (see SM 4 for details). U/Pb dating was performed by laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) at the Laboratoire Magmas et Volcans, Clermont-Ferrand, France (see SM 4 for details). The analytical results were plotted on $^{206}\text{Pb}/^{238}\text{U}$ versus $^{237}\text{Pb}/^{235}\text{U}$ (concordia)
diagrams and $^{207}\text{Pb}/^{206}\text{Pb}$ versus $^{238}\text{U}/^{206}\text{Pb}$ diagrams [Tera and Wasserburg, 1972]. A special attention was given to the rim of the crystals and to young ages, more likely to correspond to the emplacement age. Detailed data are provided in SM 5, the age populations spectra are shown in Figure SM 6, and a synthesis of the emplacement ages appears in Table 1. All early Eocene zircon grains display characteristic high Th/U magmatic values (Table SM 5).

For sample CD321-1, zircon U-Pb geochronological analyses were carried out by laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) at the State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences, Wuhan, China (see SM 7 for details).

Biotites from sample J279 were extracted in order to perform $^{40}\text{Ar}/^{39}\text{Ar}$ dating at the Rare Earth Laboratory of the geochronology laboratory of Geosciences Montpellier (University Montpellier 2, France). The irradiation factor J was determined using duplicate analyses of the TCR2 sanidine standard with an age of 28.340±0.099 Ma [Renne et al. 1998] and ages are quoted at 2σ (SM 8).

At site S224, two horizontal trachy-andesitic lava flows are interstratified within white volcanic tuffs, volcano-sedimentary levels and thin lacustrine carbonates attributed to the Shuanghe Fm (Figure 6a). Sample J121 from the lower lava flow contains K-feldspar and biotite with oxide inclusions, minor phases include apatite and euhedral zircon. Twenty-five analyses were performed on 12 zircons. Grains are homogeneous, without age difference between the crystal’s core and the rim. Except for one Ordovician grain (Figure 8a), 11 zircons (22 analyses) yield a concordant $^{206}\text{Pb}/^{238}\text{U}$ age around 35 Ma. The corresponding lower intercept on the Tera and Wasserburg diagram is 35.8 ± 0.3 Ma (Figure 8b), which we interpret as the emplacement age of the lava flow.

Most zircon grains of sample J120 from the upper lava flow have a rounded morphology, which suggests that they are inherited. Forty-three ages were calculated using 36 zircons. The ages are scattered, ranging from late Eocene to Mesoproterozoic. One single grain (not shown in the figures) is 1.5 Ga old. Eight zircons define an upper intercept on the Concordia diagram at 816 +/- 8 Ma (Figure 8c). Their high U/Th ratio indicates a magmatic event. Some zircons with ages ranging from 500 to 600 Ma are probably metamorphic grains, because their Th/U ratio is low (< 0.05). Another group (5 zircons) has a Triassic age (Figure 8d). One single grain (2 spots) is 35 ± 1 Ma old (Figure 8d). The high content of this sample in inherited zircons with various ages is consistent with the smooth morphology of the grains.
The youngest grains age at ca. 35 Ma is the closest to the emplacement age and thus yields an upper boundary for the underlying sandstone deposition (Shuanghe Fm).

At site S263, sample J203 comes from a 30-cm-thick level of a volcanic tuff interbedded within decimeter-thick sandstone and clay strata of the Shuanghe Fm. The tuff contains K-feldspar and coal fragments as well as automorphic zircon crystals. 32 analyses on 24 zircon grains showed no age difference between the cores and the rims. Grains have a high U content (> 1000 ppm). 10 zircons yield concordant ages ranging from 2.5 Ga to 51 Ma (Figure 8e, Figure SM 6). 14 zircons have Cenozoic ages with 16 analytical points out of 18 plotting at 35-38 Ma. The 18 data define a lower intercept at 36.4 ± 0.4 Ma (Figure 8f).

Sample J168A is a volcanoclastic rock that was sampled in the debris of a local coal mine (site S261 – Shuanghe Fm). It is rich in biotite, contains amphibole, K-feldspar and plagioclase. Minor phases include apatite and automorphic zircon. 38 spots were analyzed on 22 zircon grains. They have a rough content in U of 200 ppm. One single zircon shows a ~740 Ma core (Figure 8g) with a Cenozoic rim. All other grains, both in the cores and rims, are Cenozoic in age with 32 analytical data plot in a concordant position at 35-36 Ma \((^{206}\text{Pb}/^{238}\text{U}}\) age) on the Tera and Wasserburg diagram (Figure 8h). The lower intercept given by the linear regression through 34 data (2 discordant points) is 35.7 ± 0.2 Ma.

Sample J278 is a volcanodetrital rock sampled at site S805, probably near the top of the Shuanghe formation. It contains amphibole and K-feldspar, and few biotite grains. 51 zircon grains were analysed. Sample J278 yields a wide scatter of concordant ages from ~2300 to ~37 Ma. Most grains have an age of about 820 Ma (12 grains out of 51) and about 220 Ma (9 grains) (Figure 8i, Figure SM 6). The single youngest concordant age is 36.8 ± 1.0 Ma (Figure 8j).

Sample J308 (site S882) is a volcanosedimentary rock from an outcrop located in a slice of rocks between two branches of the Qiaohou fault west of the Jianchuan basin. It contains amphibole, quartz and automorphic feldspar. 10 grains out of 37 euhedral zircon grains have \(^{206}\text{Pb}/^{238}\text{U}}\) ages ranging from 245 to 849 Ma. 26 analytical points, each of them corresponding to a single grain, are concordant at ~35 Ma \((^{206}\text{Pb}/^{238}\text{U}}\) age) and define a lower intercept at 34.74 ± 0.17 Ma. (Figure 8k).

J161, sampled at site S257, is a volcanoclastic sandstone of the Jianchuan Fm (E2Jc) that contains plagioclase feldspar, pyroxene, oxide and weathered biotite. 30 analyses were performed on 20 euhedral zircons. Grains show no age difference between the core and the
rim. 17 data, corresponding to 9 zircons, define a Discordia with an upper intercept at 819 +/- 8 Ma (Figure 8I) while 8 data yield a Concordia age of 223.9 ± 2.2 Ma (Upper Triassic) (Figure 8m). 3 analytical points (2 zircons) are nearly concordant and define a lower intercept at 35.9 ± 1.1 Ma (MSWD = 1.5) (Figure 8m) that we consider as a lower boundary (maximum age) for the sandstone deposition.

Sample J284, collected at site S819, is as a boulder fallen from the overlying cliff carved in the Jianchuan Fm. It is a rhyolitic tuff that contains plagioclase feldspar, few biotite crystals and few xenoliths. 29 zircons out of 33 show U/Pb ages ranging from 1800 to 210 Ma (Figure 8n). 4 grains have Cenozoic ages and the three youngest concordant data have an average Concordia age of 34.8 ± 1.1 Ma (Figure 8n) that is a maximum age for the tuff emplacement.

Lamprophyres sampled both in the Mengyanjing formation (Sample J108, site S213) and in the Jianchuan Fm (Sample J279, site S808) both yield only pre-Cenozoic ages (Figure 8o-7p, Figure SM 6). Biotites of sample J279 yield an age spectra with ages progressively decreasing from 44 to 37 Ma and an integrated age of 39.40±0.90 (Figure SM 8a), that has probably no geological signification. This age is probably due to alteration and partial chloritization of the biotites that possibly induced 39Ar recoil during irradiation. Indeed, the K/Ca correlation plot indicates heterogeneous K distribution with low amounts at the beginning and the end of the spectra (Figure SM 8b). On an inverse isochrone plot the data appear to define several array possibly corresponding to different argon reservoirs, the one corresponding to the last 55 % of gas release yielding an age of 34.48±1.02 Ma for an initial 40Ar/36Ar ratio of ca 1474±300 and a fairly large MSWD = 7.51 (Figure SM 8c). On the age spectra these steps yield a mean weighted age of 36.60±0.61 (Figure SM 8a). The emplacement age of the dyke is interpreted to be younger than 36.60 Ma, and possibly close to ~34.5 Ma.

Sample J296 was sampled in a trachy-andesitic neck standing in the north of the basin (site S849) above the Mengyanjing Fm. It yields many inherited ages (Figure 8q, Figure SM 6) while three grains yield subconcordant ages between ~34 and ~43 Ma (Figure 8r). The youngest age (33.7 ± 0.9 Ma) could be considered as the emplacement age but the point is barely concordant and thus does not give a robust age constraint.

Sample CD321-1 comes from a granite porphyry dyke within the Jinsichang Fm and close to a diorite intrusion. It contains zircon. Few ages are pre-Cenozoic but most of these
are subconcordant at ~35 Ma (Table SM 9) (Figure 8s) and 12 of them yield a 34.73 ± 0.76 mean weighted age (n=12, MSWD = 1.5) (Figure 8t).

3.1.2. Constraints on the age of the Shuanghe Fm from interbedded deposits.

At site S224, in the Ziangchong valley, our results indicate that the lower and upper trachy-andesitic lava flows are respectively 35.8 ± 0.3 (J121) and 35 ± 1 (J120) Ma old, thus constraining part of the sedimentation of the Shuanghe Fm at ~35.5 Ma (Figure 3c). Yang et al. [2014] report a trachydacite volcanic level (sample DX-030-6) containing zircon they dated at 36.59 ± 0.67 Ma with the U/Pb method. The precise sample location is not given but appears to be ~150m east of site S224. They interpreted the trachydacite volcanic level to be interstratified in a trachyandesite level supposed to lie at the boundary between the Yunlong and Mengyanjing formations. We think that this level is in fact the same level as the one we observed at site S224 (possibly the lower lava flow). However, the lava flows they described ~2 km further to the west (site S841) are in fact sills intruded, not interstratified, at the base of the Baoxiangxi Fm (Figure 6c). We thus think that the trachydacite volcanic level(s) is not located at the base of the Baoxiangsi Fm but within the Shuanghe Fm. The fact that the age of DX-030-6 is the same within error bars of that of J121 strengthens our interpretation that the Shuanghe Fm emplaced at ~35.5 Ma (Upper Eocene).

In the Shicaijiang valley, at site S263, sample J203 (volcanic tuff) is 36.4 ± 0.4 Ma old. Hoke et al. [2014] provide a 37.1 ^{+0.78}_{-1.59} Ma U/Pb age for tuffaceous sandstone (sample JIAN-11-05) in the same area. While the precise location of their sampling is not given it appears close to S263 (Liu-Zheng, personal communication), and is compatible with our more tightly constrained age. In the same zone but ~120 m higher in the topography volcanodetritic sample J168A yields an age of 35.7 ± 0.2 Ma. J278, sampled ~2.5 km further east, yields an age of 36.8 ± 1.0 Ma.

Despite large uncertainties in relative stratigraphic position within the formation and in absolute age, the Shuanghe Fm appears to have deposited between ~37 and ~34.7 Ma, with a mean weighted average age of 35.88±0.35 Ma (weighted mean, MSWD=3.9) (Figure 3c).

Along the Qiaohou fault, a slice of rock most probably belongs to the Shuanghe Fm (Figure 2). Yang et al. [2014] report volcanoclastic sediments outcropping in that slice (sample DX039-5, site S222, Figure 2). Alike for sample J120 the zircons are rounded and yield $^{206}\text{Pb}/^{238}\text{U}$ ages spanning from 1777 to 34 Ma, the youngest four concordant dates yielding a $^{206}\text{Pb}/^{238}\text{U}$ age of 35.0 ± 2.3 Ma. At site S882, 17 km further SE, in the same slice
along the fault, sample J308 yields a 34.74 ± 0.17 Ma emplacement age that is consistent with that of DX039-5. These two ages are coherent whilst slightly younger than the other ages for the Shuanghe Fm (Figure 3c).

3.1.3. Constraints on the age of the Jianchuan Fm from interstratified deposits.

The two youngest zircons found in sample J161 (volcanoclastic) imply a maximum age of 35.9 ± 1.1 Ma for the Jianchuan Fm, while the youngest concordant data for J284 rhyolitic tuff suggest an emplacement age of 34.8 ± 1.1 Ma. This age is imprecise because most of the zircons are inherited, but the most plausible interpretation is that the Jianchuan Fm is ~35 ± 1.5 Ma (Upper Eocene) old (Figure 3c). In fact, it cannot be excluded that all zircons are inherited and that the Jianchuan Fm would correspond to a young volcanic event (Neogene) that would not have produced any new zircon. In support to such interpretation Xiang et al. [2009] reported apatite fission track (AFT) ages from the Jianchuan Basin spanning from 1.6 to 15.8 Ma. The ages of sample FT03 within the Shuanghe Fm at 15.8 ± 0.8 Ma (Miocene) and that of FT 10 in the Jianchuan Fm. at 2.4 ± 0.8 Ma (Pliocene) were interpreted as emplacement ages sustaining the conventional stratigraphy. However a closer look to the AFT data set reveals that all samples whatever the formation, except for FT03, are Pliocene including the one from the Shamao Shan syenite whose emplacement age is well constrained at 35.5 ± 1 Ma [Schärer et al., 1994 ; Lu et al., 2012] (Table SM 2). It is thus most likely that all AFT ages are cooling ages and not emplacement ages. Furthermore the authors did not yield the conventional plots that would allow checking the accuracy of their data.

3.1.4. Cross-cutting intrusive rocks.

As mentioned in section 1 and depicted in all geological maps the Jianchuan basin contains several intrusive bodies (Figure 2). These plutons cut across the Mengyanjing, Baoxiangsi and Jinsichang formations (Figure 2). The relationship with the Jiuiziyan, and Shuanghe formations is more difficult to establish as no direct contact exist with the plutonic rocks. At the top of the lithologic pile the Jianchuan formation surrounds the Shamao Shan syenite. At site S251 the Jianchuan formation appears to be intruded by the syenite as this one shows a chilled margin (Figure 6f). 600 m to the west, at site S808, the Jianchuan formation is cross-cut by a lamprophyre dyke which given its composition is likely genetically related to the nearby Shamao Shan syenite (Figure 6e). This would again suggest that the Jianchuan
formation is at least in part antecedent to the syenite, and thus that the whole sedimentation within the Jianchuan basin took place prior to the syenite emplacement.

Following the pioneering work of Schärer et al. [1994] several other studies have yield zircon U/Pb ages for the magmatic bodies of the Jianchuan basin [e.g., Liang et al., 2007; Lu et al., 2012] (SM 2, Figure 2). The Shamao Shan Syenite yielded U/Pb zircon ages of 35 ± 0.1 Ma [Schärer et al., 1994] and 35.6 ± 0.3 [Lu et al., 2012]. All eight published high-precision ages from the various intrusive bodies within the Jianchuan basin span between 34.5 and 35.7 Ma. They indicate a brief plutonic event of weighted average mean age of 35.22 ± 0.30 Ma (Upper Eocene). This age is similar within uncertainties to that proposed above for the Shuanghe formation (35 ± 1.5 Ma). The sample taken from the dyke at site S808 (J279) only yielded U/Pb inherited ages but the Ar/Ar data suggest an age close to ~34.5±1 Ma compatible to that of the other intrusive bodies.

Because we did not observe its field relationships with the Jiuziyan, Shuanghe and Jianchuan formations, and because it cannot be dated directly, the age of the Jinsichang Fm is difficult to constrain. Based on geometrical relationships between the formations that are available on the maps, the Jinsichang Fm has to be younger than the Mengyanjing and Baoxiangsi Fms. According to the maps, the Jinsichang Fm is clearly cut by at least three intrusions dated at ~35 Ma (SM 2, Figure 2). This is confirmed by the age of 34.7 ± 0.8 Ma of dyke CD321 that is intrusive within the Jinsichang Fm (Fig. 2a). Sedimentation of the Jinsichang Fm thus started prior to 35.22 ± 0.30 Ma. However, as syenite boulders are locally found within the Jinsichang Fm (site S556), it suggests that sedimentation and emplacement of the intrusions was partly coeval and that sedimentation lasted until some portions of the plutonic bodies were eroded.

3.2. Palaeontological remains

At site S603, near the Dongfengping village (Figure 2) local people discovered well-preserved mammal dental remains in yellow sandstones interbeded with coal deposits of the Shuanghe Fm. The left hemimandible includes two well-preserved molars (m1-m2, Figure 6b). An isolated left lower third premolar (p3) and a right fourth premolar (p4) were also found in the same locality. Due to compatible patinae, morphological features, and tooth wear, all these specimens were most likely belonging to the same adult individual. Features such as the huge dental size, the extreme reduction of p3, the presence of flat ectolophids, the
strong obliquity of lophids, and the moderate crown height point to a giant amynodontid rhinocerotoid, further referable to *Zaisanamynodon* [Belyaeva, 1971; Lucas and Emry, 1996; Lucas et al., 1996]. This genus corresponds to a giant hippo-like amynodontine, thus far restricted to the late Eocene Ergilian Asian Land Mammal Age in China, Kazakhstan, and Japan [Tsubamoto et al., 2007]. In Yunnan, the Ergilian interval (37.2 to 33.9 Ma) yields a rich and diversified mammalian assemblage [BGMRYP, 1990] including *Zaisanamynodon* [Lucas and Emry, 1996]. This age interval is in full agreement with the one proposed above for the Shuanghe Fm from the absolute ages (35.3±0.47 Ma), but is in contradiction with the paleontological constraints previously proposed (Figure 3).

4. Implication on Eocene Tibet evolution

The Jianchuan basin was considered to be the only large sedimentary basin spanning the whole Cenozoic in a key area between SE Tibet and the Yunnan highlands. Consequently, it has been the target of several studies aiming at constraining the palaeoenvironmental, latitudinal and altitudinal evolution of the area. Furthermore, the relationship of the Jianchuan sediments with a possible paleo-course of the Yangtze river, which first bend is only ~30 km to the north, has been extensively discussed. All these studies needed robust age constraints but rested on the conventional stratigraphy. Below we discuss the implication of the new stratigraphy proposed in this study.

4.1. Implications on tectonics of SE Tibet.

4.1.1. Timing of deformation phases.

Our study evidences three main stratigraphic unconformities: first at the bottom of the Jinsichang (E2js) – Jiuziyan (E2jz) Fms, second below the Jianchuan (E2jc) Fm, and third at the base of the Sanying (N2s) Fm (Figure 2).

The third unconformity has been extensively described and corresponds to sedimentation in basins located at the footwall of faults that are still active today and that corresponds to the last phase of deformation in the area with the Red River fault dextral and N-S normal faults [e.g., Leloup et al. 1995] since ~10 – 5 Ma [e.g., Leloup et al., 1993; Leloup et al., 2001; Replumaz et al., 2001].

Regarding the first and second unconformities, only the base of the Jianchuan Fm is a clear angular unconformity, with stratifications below sometimes showing dips ≥70° and
stratifications above monoclinaly dipping ~20° to the east (section A-B, Figure 5). Below the unconformity, the steeply dipping stratification planes (≥45°) do not show any preferential direction (Figure 7a). This could result from several folding phases. For example three directions of folding (N-S, NE-SW, and NW-SE folds) could explain the data. However these three phases would have affected all formations below the Jianchuan Fm, which implies they took place in a very short time interval (<<1 Ma). It is more likely that many strata were tilted at the vicinity of the intrusives, rendering a precise analysis of the fold axis meaningless. However, along the Shicaijiang valley a ~1800m-long section exposes an anticline affecting all sediments below the Jianchuan formation. When plotted together the stratification planes imply a fold axis dipping ~7° to N5° (Figure 7b). This direction is parallel with the overall N-S direction of folds that, according to the regional geological maps [i.e., BGMRYP, 1990], affect both the Mesozoic and Eocene sediments. Such folds imply an ~E-W direction of shortening, which is compatible with left-lateral motionalong the ASRR shear zone that was active in the Oligo-Miocene [e.g., Leloup et al., 1995; 2001]. The age of ~34.5±1.0 Ma of the Jianchuan Fm implies that the ~E-W shortening was ongoing just prior to that age, coevally with magmatism. A synthesis of the ages of the ultra-potassic magmatic rocks on both sides of the ASRR shows that they emplaced between 32.5±0.3 and 36.9±0.3 (36 U/Pb data, average 35.1±0.3 Ma, Table SM 2). They thus emplaced in a very brief time interval (≤5 Ma) during ~E-W compression. In the area, significant normal faults initiated much latter (≤ 10 Ma) and are not linked with that phase of magmatism. When the original shape of the magmatic province is restored by matching the PhanSiPan intrusives with the Jianchuan ones (~600 km of left-lateral offset along the ASRR) [e.g., Leloup et al, 2001] it appears as a zone ~200 km in diameter and where ages are older in the centre (Beiya) than in the periphery. This magmatic province has been interpreted to be the eastern prong of the Qiangtang Cenozoic magmatism (Fig. 1a), suggesting a common origin (e.g. Lu et al., 2014). However, the Qiangtang magmatism starts much earlier (~45 Ma) and is on the other side of the Triassic Jinsha suture. The geometry of the Upper Eocene magmatic province together with the concomitance with the E-W compression are barely compatible with a large-scale lithospheric delamination [Chung et al., 1998, 2005, Lu et al., 2012], and are incompatible with a continental subduction along the ASRR – Jinsha suture zone to generate the Eocene magmatism [Wang et al., 2001, Ding et al., 2003]. The first hypothesis would rather require extension, while the second would rather require NE-SW shortening along the whole length of the ASRR and magmatism limited to the north of the ASRR (upper plate).
4.1.1. Implications on paleomagnetic studies.

Tong et al. [2015] have collected samples in 21 sites (JL 1-21) in red siltstone within the Jianchuan basin that they attribute to the early-middle Eocene Guolang formation (our Mengyanjing Fm). These sites yield a high magnetic component that reflects a prefolding primary remanence (DS=29.7°, Is= 32.0°, K=44.9, α95=5.6°). 14 other sites (SJ1-14) correspond to the Jinsichang formation (E2js), and yield a high magnetic component that also appears to reflect a prefolding primary remanence (DS=200.9°, Is= -31.3, K=52.8, α95=7.7°). These two directions are antipodal in good accordance with the fact that a short time probably elapsed between the deposition of the two formations and that the Jinsichang is not Oligocene but predates 35±1Ma. As these directions are Eocene they can be compared with that obtained by Sato et al., [2001] in the Eocene Lamping and Yunlong basins located south of the ASRR (D= 266.13, I =339.83 with K95 =11.23). That comparison implies a large clockwise rotation of 65.3±12.5°, and southward motion of 5.7±7.5°, of the Lamping/Yunlong area with respect to Jianchuan. When compared with results from other Cenozoic basins north of the ASRR, the paleomagnetic results imply no latitudinal motion, and limited rotation (≤20°), with respect to Jianchuan. Such results are compatible with the previous paleomagnetic studies conducted on older sediments that advocate for a large extrusion of the Indochina block south of the ASRR in the Cenozoic [e.g., Yang et al, 1995; Cogné et al., 2013]. However the uncertainty in paleolatitude is so large that the amount of post Eocene extrusion cannot be quantified from the data of the Jianchuan basin.

4.2. Palaeoenvironmental implications

4.2.1. Paleoenvironmental evolution of the Jianchuan basin during the late Eocene

Five main phases can be distinguished in the late Eocene evolution of the Jianchuan basin: (i) Suspension fallout occurred in a floodplain environment (i.e. low-energy depositional system) (Mengyanjing Fm). Red strata are occasionnally interbedded with sheet-like sandstones (overbank deposits) and/or pebble/cobble conglomerates corresponding to alluvial-fan debris-flow deposits, especially near the eastern margin of the basin. However, no lacustrine deposits were found in the Mengyanjing Fm. Occurrence of carbonate levels as thin carbonate layers and channelized structures are rather indicative of palustrine conditions and carbonate-fill stream channel deposits, respectively (e.g., floodplain deposits). (ii) A large braided-fluvial system flowing in a piedmont environment developed on a low-relief
topography, possibly merging with another river near the Diancang Shan. Our observations match with former reconstructions suggesting that the paleodrainage network of southeastern Tibet possibly resembled the large-scale dendritic patterns observed in continental interiors developed in areas of low regional relief [Clark et al., 2004]. However, albeit our interpretation (e.g., a braided-fluvial system) is not at odds with the reconstructed depositional pattern of Wei et al. [2016], neither braid-delta and delta-front macroforms, nor lacustrine/turbiditic facies deposits were observed in the Baoxiangsi Fm. Moreover, regular occurrences of siltstones interbedded into dark finer facies (e.g., mudstones/marls) most likely belong the overlying Jiuziyan and Shuanghe Fms in which definite palustrine-lacustrine (and associated floodplain) depositional environments are evidenced [Sorrel et al., submitted], but are never observed in the Baoxiangsi Fm. Hence, though more paleocurrent restoration data would help to better constrain palaeo-flow directions in the Baoxiangsi Fm, our fieldwork study does not support Wei et al.’s [2016] conclusions contending that no large fluvial system flowed through the Jianchuan basin during the timespan of the Baoxiangsi Fm. In any event, the depositional processes and sedimentary dynamics characteristics of the Boaxingsi Fm, i.e. a large braided-river system made of stacked-fluvial bars possibly flowing in a piedmont environment proximal to a local relief, are not compatible with palustrine-lacustrine conditions, which thus occur later in the succession. Ages of these two formations (i.e., Mengyanjing and Baoxiangsi Fms) are not constrained from our work unless they are older than ~35 Ma. Regional correlations suggest they are Paleocene-Eocene in age. (iii) At ~35 Ma, the braided fluvial system is deactivated following a large-scale drainage reorganization (see Section 4.2.2). Consequently, the Jianchuan basin filled-up, and the sedimentation was restricted to more local depositional settings with (1) palustrine-lacustrine (e.g., near-shore) environments (Jiuziyan Fm) evolving into swamps (Shuanghe Fm) to the east of the basin, while (2) medium to distal alluvial fans delivering detritus prevailed from both western (Jinsichang Fm) and eastern (Jiuziyan Fm) basin margins. This sedimentary succession, as well as the progressive occurrence of coal-bearing beds, is also indicative of a stepwise pattern of environmental change interspersed with climatic change and the onset of moister conditions in the Jianchuan basin [Sorrel et al., submitted], coevally to the first volcanic eruptions occurring at ~35Ma. (iv) At ~35 Ma, a large episode of plutonism occurred, leading to the deposition of volcanoclastic sediments at the surface (Jianchuan Fm) and of large plutons at depth. This episode probably lasted less than 1 Ma and was over by 34 Ma. Since then, sedimentation in the Jianchuan basin has been very limited. (v) The activation of the left-lateral / normal Jianchuan fault induced the formation of limited Pliocene (Sanying Fm)
and Quaternary basins in its hanging wall (east), and possibly enhanced erosion in its footwall (west). We do not dispose of direct age constraints for the Jianchuan Fault initiation but is part of the Lijiang – Dali pull-apart basin between the Zhongdian and Red River active dextral faults (Fig. 1b) [i.e. Leloup et al., 1995]. The Diancang Shan normal fault, 50 km to the SE, initiated at ~5 Ma [Leloup et al., 1993], possibly providing an age for the initiation of the Jianchuan fault.

4.2.2. Implication on provenance studies and river network reorganization

20 km north of the basin flows the major Yangtze River (Figure 1b). Its peculiar hairpin shape (called the Yangtze first bend) has intrigued geologists for decades. Recent studies [Clark et al., 2004, Kong et al., 2012, Wang et al., 2013] seem to confirm the first hypothesis of Barbour [1936] who thought that the Yangtze River was flowing southward and was connected to the Red River, at the location of the Jianchuan basin, before experiencing a reorganization of its course. However, the connection between the paleo-Yangtze and the Red River via the Jianchuan area is disputed [e.g., Wei et al, 2016], as well as the timing of the drainage reorganization; it ranges from the Pleistocene [Kong et al., 2013] to the Eocene [Zeng, 2002]. Several studies focusing on this problem are based on sediments from the Jianchuan basin.

Yan et al. [2012] assess the river reorganization in SE Tibet by tracing the source of the sediments of the Jianchuan basin. To do so, they compare zircon U/Pb ages of potential bedrock sources and sand from the modern Yangtze river, to detrital zircon U/Pb ages of the Baoxiangsi Fm (sample JSJ150), the Jinsichang Fm (sample JSJ18), the Shuanghe Fm (sample JC13) and the Jianchuan Fm (sample JC18). Yan et al. [2012] suggest a major change in the sediment provenance; the source of the Baoxiangsi Fm belonging to the North China block (Songpan-Garze) whereas the source of the sediments of the Jinsichang, Shuanghe and Jianchuan Fm would be more local belonging to the South China block and Yidun arc. They relate this change to a change in the course of the Red River in late Oligocene, possibly linked with the onset of strike-slip faulting along the ASRR shear zone. Using our revised stratigraphy, the drainage change proposed by Yan et al. [2012] would have occurred prior to ~35 Ma not in the late Oligocene (~23 Ma) as previously thought. This could imply that the ASRR left-lateral motion started during late Eocene time as suggested by some studies [e.g., Leloup et al., 2001, 2007].
Wei et al. [2016] assess the same problem with a different approach; to reconstruct the river network evolution, they restore paleoflow directions in the Baoxiangsi and the Jinsichang Fm. Combined with a sedimentology analysis of sediments outcropping in the Jianchuan basin and collected in drill holes in the Dianwei basin, Wei et al. [2016] conclude the Yangtze first bend, *i.e.* the Yangtze River modern course, was set up during the late Miocene or later. Although our findings do not necessarily contradict the paleoflow restoration of Wei et al. [2016], their estimated timing for the establishment of the upper Yangtze River has to be reevaluated. The authors consider the Baoxiangsi Fm as formed in an internally drained basin, whereas there is no evidence of internal drainage in the sedimentary record. Wei et al. [2016] use the top of the Shuanghe Fm (being attributed to the Oligocene based on the BRGMY [1990] stratigraphy) as a lower boundary for the establishment of the modern river configuration, the argument being that lacustrine sediments from this formation are not compatible with a major river such as the Yangtze River. Based on the revised late Eocene age of this formation and our interpretation of the sedimentary facies, the Jianchuan area probably experienced a change in its drainage system during the late Eocene.

Indeed, our results evidence an abrupt decrease in sedimentation at the end of the Eocene. This can be related to a river network reorganization, although other potential factors such as climate evolution could be at play. The latest major stage of sedimentation seems to coincide with the paroxysm of the volcanic activity in the area. It is then tempting to consider a cause and effect relationship between both events, as hypothesized by Zeng [2002]. Braided river sediments are generally related to a moderate regional slope. The appearance of eruptions and multiple volcanic bodies might have been sufficient enough to locally modify this slope, thus leading to a possible change in the river network. Alternatively, tectonic activity, *e.g.* the ASRR shear zone, could be responsible for this change. Today, the upper Yangtze flows parallel to the ASRR shear zone and its drainage system is clearly deflected by active strike-slip faults, such as the Zhongdian left-lateral fault (*Figure 1b*). As mentioned above, the left-lateral motion of the ASRR shear zone started between 36 and 28 Ma; this age range overlaps the end of the sedimentation in the Jianchuan basin. Although this study does not allow assessing the potential connection between the Paleo-Yangtze and the main river that used to flow in the Jianchuan area, both were likely affected by the motion on the ASRR shear zone.

### 4.3. Implication on paleoelevation studies
Several studies focus on the elevation evolution of eastern Tibet [Hoke et al., 2014; Jacques et al., 2014; Li et al., 2015]. The main objective was to reconstruct the onset of this part of the plateau uplift. This timing can thus be compared with the age of the India-Asia collision and of the central Tibetan plateau uplift. Then models of Tibetan plateau development and propagation can be tested. Many of these studies are based on stable isotope paleo-altimetry on carbonates (lacustrine and paleosol) and require (1) a robust constrain on the age of the sampled formation, (2) an estimate of the Mean Annual Air Temperature (MAAT) to convert the oxygen isotopes composition of the carbonates ($\delta^{18}O_{\text{carb}}$) to the one of the precipitation ($\delta^{18}O_{\text{p}}$), (3) the surface water oxygen isotopic composition at low elevation along the moisture path and (4) an appropriate surface water oxygen isotopic composition – elevation relationship [e.g. Poage and Chamberlain, 2001; Rowley, 2007; Rowley & Garzione, 2007]. Two studies have been performed in the Jianchuan basin, based on lacustrine and paleosol carbonates from the Shuanghe Fm. [Hoke et al., 2014], and Jiuziyan Fm. [Li et al., 2015]. Hoke et al. [2014] propose a 3300+/−1000m elevation during late Eocene time, while Li et al. [2015] propose a 2600 +800/−1100 m elevation for Miocene time. To convert the $\delta^{18}O_{\text{carb}}$ to $\delta^{18}O_{\text{p}}$ both studies use the Sun et al. [2011] MAAT estimates based on paleobotanic studies of the Shuanghe formation that was previously ascribed to the Miocene. Li et al. [2015] apply a conservative +5°C correction to take into account the temperature difference between lake water and MAAT. Hoke et al. [2014] recognize a late Eocene age for their studied pedogenic carbonates and then use the MAAT from Sun et al. [2011] with a +10°C correction to account for the warmer Eocene climate. The revised stratigraphy implies that the Sun et al. [2011] MAAT estimates on the Shuanghe formation does not apply to Miocene time but rather to late Eocene. Thus the $\delta^{18}O_{\text{p}}$ calculation of Li et al. [2015] applies to the lower Eocene and the +10°C correction applied by Hoke et al. [2014] is not justified. Moreover, Li et al. [2015] used a modern oxygen stable isotope versus elevation relationship rather than the Eocene calibration, resulting in an underestimate of paleo-elevation (Figure 9). The new stratigraphic age possibly also influences the $\delta^{18}O_{\text{p}}$ at low elevation along the moisture path that is required for paleo-elevation calculations. Li et al. [2015] use a $\delta^{18}O_{\text{carb}}$ from Miocene paleosol of the western Siwalik [Quade & Cerling, 1995] that they convert into a $\delta^{18}O_{\text{p}}$ of -6.6 +/- 1.4‰ VSMOW. We rather use the $\delta^{18}O_{\text{p}}$ (-8.2 +/- 1‰ VSMOW) reconstructed from late Eocene gastropods sampled in Myanmar [Licht et al., 2014]. Such choice is also consistent with Licht et al. [2014] modeled Eocene moisture paths. Thus, we combine the $\delta^{18}O_{\text{p}}$ calculated from lacustrine and paleosol carbonate of Li et al.
and Hoke et al. [2014] that we ascribe to late Eocene time with the late Eocene δ\textsuperscript{18}O\textsubscript{p} estimated in Myanmar and apply the Eocene oxygen stable isotopes versus elevation calibration of Rowley [2007]. The obtained late Eocene paleo-elevation for the Jianchuan basin is then of 2800 +/- 1000m, which is similar with previous studies (Figure 9). However, this calculation does not take into account the continentality effect. Along the moisture path, the δ\textsuperscript{18}O\textsubscript{p} decreases inland of about 2‰ / 1000 km [Rozanski et al., 1993]. Li et al. [2015] consider that the Jianchuan basin was 150 km inland to calculate this correction. However using the plate reconstruction of Replumaz & Tapponnier [2003] at ~40Ma the distance between the Myanmar reference site and the Jianchuan basin is of about 1500km, resulting in a -2.5‰ correction. The corrected paleo-elevation is then of 1200+/-1200m (Figure 9). In conclusion, the revised stratigraphy has multiple implications on paleo-elevation calculations. The revised estimates suggest that in late Eocene time, the Jianchuan area may have been at low elevation or at least at a lower elevation that in present time. This implies that significant uplift may have occurred only after late Eocene time.

Conclusion

A new stratigraphy is proposed for the Jianchuan basin. Sandstone, siltstone and mudstone beds of the lowest Menyanjing formation (E1m) correspond to a floodplain environment. They are overlain by the massive sandstones of the Baoxiangsi Fm (E2b), which corresponds to a wide braided-fluvial system. Above this are the Jiuziyan Fm (E2jz) limestones that deposited in the eastern part of the basin in a lacustrine-palustrine environment, and the Jinsichang Fm (E2js) sandstones and breccia in the western part of the basin that correspond to alluvial fans. The Jiuziyan Fm is overlain by the Shuanghe (E2s) sandstones and coal deposits. The appearance of coal-bearing beds in the Shuanghe Fm suggests that stepwise environmental change occurred in the Jianchuan basin. These modifications were interspersed with climate change and the onset of moisture conditions. The Jiuziyan, Jinsichang, and Shuanghe formations correspond to the filling of the basin after the deactivation of the main river system, due to a large-scale drainage reorganization. Potential causes for this river network modification are the initiation of the left-lateral Ailao Shan – Red River shear zone and/or the brief high K magmatic event that occurred in SE Tibet, including in the Jianchuan basin. The Jianchuan Fm (E2jc) volcanosedimentary deposits rest above all formations through an angular unconformity. ~E-W shortening affected the basin prior to the deposition
of the Jianchuan Fm. After deposition of the Jianchuan Fm, sedimentation was extremely limited and controlled by the active normal Jianchuan fault.

Sedimentation of the Shuanghe Fm occurred during a short time lapse (35.88±0.35 Ma) in part coevally with the magmatic event (35.22 ± 0.30 Ma). These late Eocene absolute ages are confirmed by the discovery of dental remains of Zaisanamynodon Belyaeva, 1971, a large amynod rhinocerotoid that lived in Asia during the Ergilian (Upper Eocene, 37.2 to 33.9 Ma).

Sedimentation of the Jinsichang Fm started prior to 35.22 ± 0.30 Ma. The age of the Jianchuan Fm is close to that of the underlying formations (~35 ± 1.5 Ma).

High K magmatism is contemporaneous from ~E-W shortening that affected a ~200-km-wide area. The Ailao Shan-Red River shear zone later led to a left-lateral offset of ~600 km of this area. Our reconstruction is barely compatible with models of large-scale lithospheric delamination [Chung et al., 1998, 2005, Lu et al., 2012] and in contradiction with models of continental subduction along the ASRR – Jinsha suture zone [Wang et al., 2001, Ding et al., 2003] that have been proposed to explain that magmatism.

Previous high paleoaltitude estimates for the Jianchuan basin [Hoke et al., 2014; Li et al., 2015] using the conventional stratigraphy have to be re-evaluated. The paleosol and lacustrine carbonate stable oxygen isotopic composition measured by Hoke et al. [2014] and Li et al. [2015], when affected to the new age and corresponding proper corrections (MAAT, moisture path, low elevation isotopic composition, continentality effect) yield a paleo-elevation of 1200+/−1200m suggesting that uplift of the Jianchuan basin took place after ~35 Ma.

This study highlights an often neglected problem: continental sediments are difficult to precisely date but determining their age is fundamental to properly unravel the structural evolution of continents.

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Table captions

Table 1 Main sites cited in text together with Cenozoic geochronologic ages from this study and those of comparable samples available from the bibliography. All sites appear on Figure 2.

Figure captions

Figure 1. a) Topographic map of Tibet with main faults (black), suture zones (green) and Eocene ultra K magmatism (red). The frame corresponds to b. b) Simplified geological map of the SE edge of the Tibetan plateau with location of the major faults and main Cenozoic and Quaternary sedimentary basins. The grey box indicates Figure 2 location. Tectonic features are after Leloup et al. [1995].

Figure 2. Structural map of the Jianchuan area based on existing maps revisited after new fieldwork including new stratigraphic and structural interpretations. Main sites (stars) are located as well as some geochronologic ages with numbers referring to bibliography: (1) Schärer et al. [1994]; (2) Yang et al. [2014]; (3) Lu et al. [2012]; (4) Liang et al. [2007]. Other results are from this study. The inset in the lower-left corner depicts the geometrical sedimentary relationships between the formations, with blanks corresponding to sedimentation gaps and undulations to angular unconformities (see text for details). Magmatic rocks lithology: ξ syenite, δ diorite, γ granite, η norite, τ trachyte. A version of this map without ages is given as SM 8.

Figure 3. Comparison of concurring stratigraphies proposed for the Cenozoic Jianchuan basin. a) Conventional stratigraphy modified from BRGMY [1990]. b) Revised stratigraphy [This study]. c) Absolute ages of deposits interstratified within the Shuanghe Fm (Table 1, SM 2). A complete comparison is given in SM 3.

Figure 4. Field pictures illustrating some sedimentary formations. a) Massive sandstones (Baoxiangsi formation) on top of siltstones from the Mengyanjing formation, with local bioturbation evidence. b) Megaripple, Baoxiangsi formation. c) Detail of b) showing downstream accretion towards the palaeoflow direction foresets (red dotted line) in fine fluvial sands. The upper dotted line shows a reactivation surface over underlying deposits. d) Multi-storey sandstones composed of vertically amalgamated channel-fill geometries and stacked-fluvial bars at Shibaoshan Temple (site CD126). e) Limestones of the Jiuziyan
formation. f) Limestones of the Jiuziyan formation resting on top of red siltites of the Mengyanjing formation (site S607). The black frame corresponds to g) g). Detail of f) showing the basal conglomerate.

**Figure 5.** Geologic cross sections corresponding to the gray lines on Figure 2. Geologic formations colors are shaded when inferred above topography.

**Figure 6.** Field pictures illustrating some age constrains. a) White volcanoclastic sandstone level of the Shuanghe formation (Site S224) interbedded between two trachytic lava flows. b) Dental remains of *Zaisanamynodon* found at site S603 within the Shuanghe formation. c) Lamprophyre sill intruding the base of the Baoxiangsi formation (site S841). d) Lamprophyre sill within a Shuanghe formation coal level (site S802). e) Lamprophyre dyke cutting across the Jianchuan formation (site S808). f) Contact zone of the Shamao Shan syenite with the Jianchuan formation (site S251).

**Figure 7.** Stratigraphy attitudes within the Jianchuan basin. Schmidt lower hemisphere projections were performed using stereonet 6.3.3 [Allmendinger et al., 2012], showing stratification (great circles) and poles to stratification (dots). a) All measurements from Mengyanjing (E1M - red), Baoxiangsi (E2b – orange), Jinsichang (E2js – pink), Jiuziyan (E2jz – blue) and Shuanghe (E2s – yellow) formations. b) Measurements from the anticline within the Shicaijiang valley (sites S259 (E2jZ – blue), S564 (E2jZ), S800 (E1M - red), S567 (E2jZ), S568 (E2S - yellow), S569 (E2S), and S570 (E2S)) and the overlying Jianchuan formation (S258, S806 and S808 - brown). The plane that best fits with the stratification poles is in red and its pole corresponding to the fold axis (N7 5) is a red square.

**Figure 8.** New zircon U/Pb dating results, with $^{206}$Pb/$^{238}$U vs $^{207}$Pb/$^{235}$U Concordia diagrams on the left and $^{207}$Pb/$^{206}$Pb vs $^{238}$U/$^{206}$Pb Terra and Wasserburg diagrams on the right, for each samples J121 (a, b), J120 (c, d), J203 (e, f), J203 (g, h), J203 (i, j), J296 (q, r). For sample J308 only the Terra and Wasserburg diagram is shown (k). For samples J168, J284, J108, and J279 only the Concordia diagram are shown (l, n, o, p). For sample CD321-1 the Terra and Wasserburg diagram is shown on the left and the mean average age on the right (s, t), errors are reported at the 1σ level, and on s dashed data are not taken into account in the age calculation.

**Figure 9.** Reconstructed paleo-elevation of the Jianchuan basin in the late Eocene. The Eocene $\Delta\delta^{18}O_p$ vs elevation relationship (back curve) of Rowley [2007] has been used. Modern relationship (dashed curve) of Rowley [2007] implying lower elevations for similar
δ¹⁸Oₚ is plotted for comparison. Δδ¹⁸Oₚ is the difference between δ¹⁸Oₚ at the studied site and δ¹⁸Oₚ at low elevation along the moisture path. The empty black rectangle corresponds to the paleo-elevation estimate without taking into account the continentality effect correction while the grey rectangle was obtained using a -2.5‰ correction. Hoke et al. [2014] and Li et al. [2015] paleo-elevation estimates are plotted on the left for comparison. See text for details.

Supplementary Material

SM 1 Structural map of the Jianchuan basin (.kmz file).

SM 2. Geochronologic ages for the Jianchuan formation and alkaline plutonic rocks in Yunnan and Vietnam.

SM 3. Comparison between the various stratigraphies proposed for the Jianchuan basin.

SM 4. Analytical techniques for U/Pb dating (LMVC).

SM 5. Detailed U/Pb results for samples J121, J120, J203, J168A, J278, J308, J161, J284, J108, J279 and J296.

SM 6. Relative probability density plot of zircon U/Pb ages for each sample. Only data more than 95% concordant are plotted.

SM 7. Analytical techniques for U/Pb dating for sample CD321-1 (Wuhan).

SM 8. ⁴⁰Ar/³⁹Ar data, sample J279. a) Age spectrum, b) K/Ca spectrum, c) inverse isochrone, d) data table.

SM 9. Detailed U/Pb results for sample CD321-1.
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