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Late Cretaceous–Palaeogene topography of the Chinese Tian Shan: New insights from geomorphology and sedimentology

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ABSTRACT

The Cenozoic growth of the intra-continental Tian Shan Range initiated during the late Eocene–Oligocene, and led to a tectonic reactivation of the complex Palaeozoic and Mesozoic lithospheric structure. Due to the very low erosion rates linked to the semi-arid climate that characterised the Tian Shan region during most of the Cenozoic, the topography of the range is not at equilibrium with deformation. Fragments of pre-orogenic low relief surfaces are preserved among the Late Cenozoic Alpine-type topography. Using field observations and satellite image mapping of those fragments, as well as sedimentology and biostratigraphic analysis, we show that the pre-Oligocene topography of the Tian Shan region was indeed complex, combining hundreds of metres to one-and-a-half kilometre-high reliefs with a multi-phased Mesozoic planation surface incised by Late Mesozoic paleo-valleys. The occurrence of several metres-thick Late Cretaceous–Palaeogene calcareous paleosols, in the basins surrounding the range further implies a semi-arid climate, very low subsidence rates and no uplift at that time. Late Cretaceous and early Miocene fossil records in the northern Tian Shan suggest a possible connection, even if episodic, between the drainage system of the south Junggar foreland basin and the proto-Paratethys Sea to the west. A renewed late Eocene–early Oligocene sedimentation probably marks the onset of the Tian Shan uplift. We argue that in addition to the growth of the Pamir and Western Kunlun ranges, this incipient uplift was one of the driving mechanisms for the final retreat of the proto-Paratethys Sea from the Tarim Basin. This regression apparently did not change the climate in the studied area because semi-arid conditions seem to prevail at least since the Late Cretaceous. Finally, the Tian Shan uplift remained very limited up to the Miocene as revealed by the occurrence of Burdigalian lake deposits preserved in the paleo-valleys inside the present day range. In contrast, post-early Miocene deformation of the northern Tian Shan has produced 4000 to 5000 m of differential vertical movement between the uplifted range and the subsiding proximal foreland basin.

1. Introduction

Many studies dealing with the topographic evolution in active mountain ranges focus on understanding and quantifying the distribution of surface uplift and erosion through time (Clark et al., 2006; Finnegan et al., 2008; Liu-Zeng et al., 2008; Ouimet et al., 2010; Sugai and Ohmori, 1999; Wang et al., 2014). These constraints are also crucial to decipher the feedbacks between tectonics, erosion and climate. However, the occurrence of a pre-existing relief or an antecedent hydrographic network within a range has implications on the calculated amount of surface uplift and erosion. These initial topographic features also influence the assessment of rock uplift, drainage evolution and sediment sources, as well as of the regional climate dynamics (e.g. orographic effects linked to inherited relief may pre-date the studied period). Consequently, documenting the initial topography of an orogen brings valuable insights on range evolution and landscape dynamics (Burbank et al., 1999; Hetzel et al., 2011).

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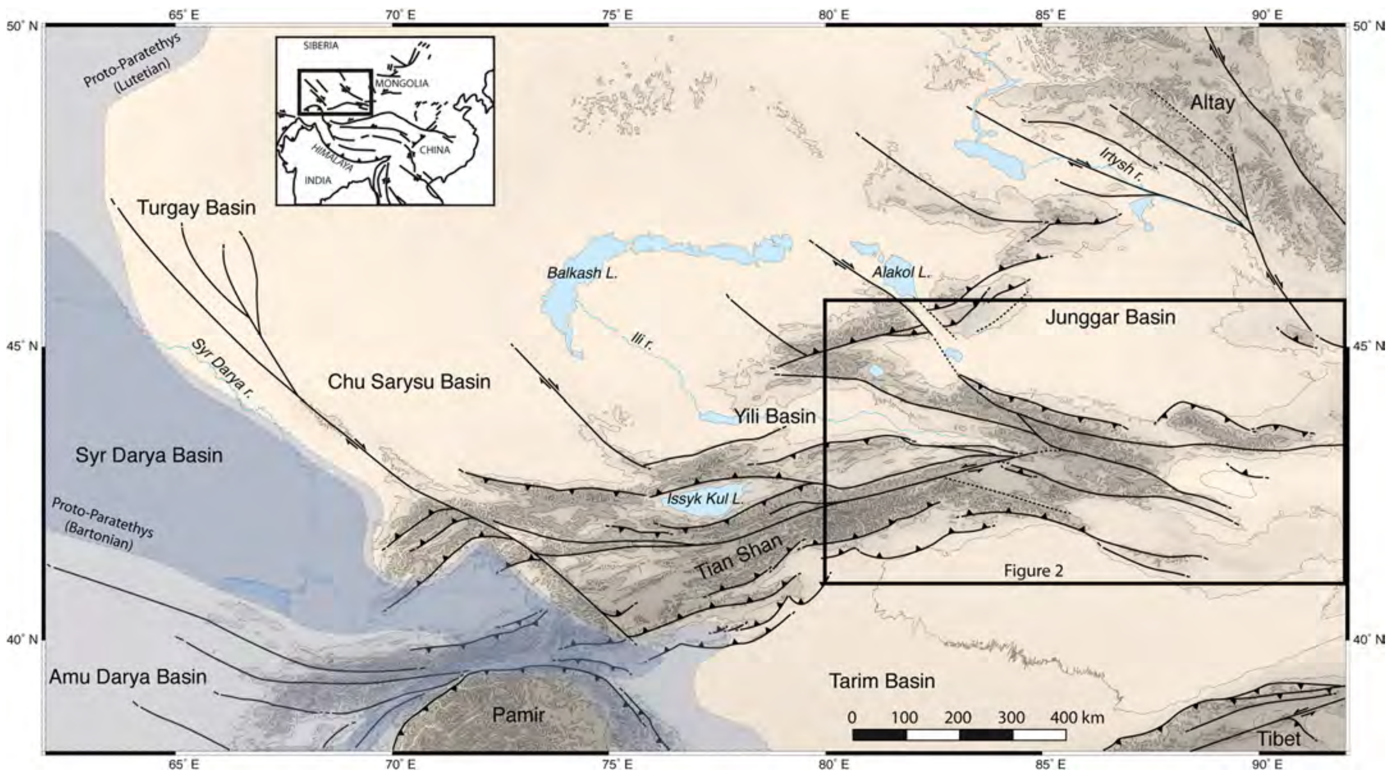

Fig. 1. General geographic and structural framework of the Tian Shan Range. The areas shaded in grey indicate the extent of the proto-Paratethys Sea during the two last transgression events in the Lutetian and Bartonian (Bosboom et al., 2014, 2017). Note that these envelopes are defined on the actual topography and that the extension of the sea towards the Pamir area is unknown. (For interpretation of the colours in the figure(s), the reader is referred to the web version of this article.)

In Central Asia, the intra-continental Tian Shan Range is a complex, multi-phased orogenic belt that was reactivated from the late Oligocene in response to the India–Asia collision (Avouac et al., 1993; De Grave et al., 2012; Dumitru et al., 2001; Tapponnier et al., 1986) (Fig. 1). The Cenozoic deformation is superimposed on and reactivates inherited Palaeozoic and Mesozoic lithospheric structures (Dumitru et al., 2001; Buslov et al., 2007; Jolivet et al., 2010 (see below)). Largely due to the semi-arid climate conditions that seem to prevail in Central Asia during most of the Cenozoic, the topography of the range still contains topographic features that existed prior to the onset of the Cenozoic orogeny (Dumitru et al., 2001; Guerit et al., 2016; Charreau et al., 2017). Our study focuses on geomorphic analysis of key relics of this paleo-topography preserved within the northern Chinese Tian Shan, as well as on analysis of Palaeogene to Miocene sediments exposed both within perched paleo-valleys in the range and in the Tarim and Junggar basins (Fig. 1). We show that the pre-Oligocene Tian Shan already had a structured topography. During the Palaeogene, thick calcrete layers indicate very low subsidence rates in the surrounding basins, a seasonal semi-arid climate and an absence of strong vertical tectonic movement.

2. Overview of the Mesozoic tectonic and topographic evolution of the Tian Shan Range

Following the Late Carboniferous–Early Permian final accretion of various continental blocks and arc-type terranes (Charvet et al., 2011; Wang et al., 2007), the paleo Tian Shan Range was affected by a major Early Permian to Early Triassic transcurrent tectonic regime that reactivated the main Late Carboniferous–Early Permian structures. This episode induced major exhumation and relief building in the range as well as the formation of pull-apart basins along the major strike-slip faults (Allen et al., 1995; Dumitru et al., 2001; De Jong et al., 2009; Jolivet et al., 2010; Yang et al., 2013). The Triassic to Jurassic period was then characterised by slow basement exhumation indicative of a progressive relief decrease (Dumitru et al., 2001; De Grave et al., 2007; Jolivet et al., 2010; Li et al., 2010). Extensive Lower to Middle Jurassic coal deposits in the Tarim and Junggar basins further suggest flat depositional landscapes with limited detrital input into the basins surrounding the range (Hendrix et al., 1992). However, the Triassic to Jurassic period was also marked in the Tian Shan region by discrete, mostly compressive tectonic events essentially linked to the accretion of the Cimmerian blocks along the southern margin of Asia (Allen et al., 1991; Hendrix et al., 1992; Allen and Vincent, 1997; De Grave et al., 2007; Yang et al., 2013). During the Cretaceous, renewed compressive deformation in the Tian Shan area is evidenced from basement cooling (De Grave et al., 2007; Glorie et al., 2010) and basin inversion (Hendrix et al., 1992; Li and Peng, 2010; Yang et al., 2013), possibly driven by the Early Cretaceous accretion of the Lhasa block along the southern margin of Tibet (Kapp et al., 2007) and by the closure of the Mongol–Okhotsk Ocean in Siberia (Zorin, 1999). Nonetheless, these tectonic movements and associated exhumation–erosion processes have been limited enough to allow the continuous development of the still preserved Mesozoic planation surface, although they most probably reworked it, leading to multi-phased nested surfaces rather than to a continuous one.

3. Preserved fragments of a Mesozoic–Early Cenozoic topography

3.1. Basement-cut planation surfaces in the Tian Shan range: overview

Numerous fragments of basement-cut planation paleo-surfaces are exposed within Central Asia (Berkey and Morris, 1924; Allen et al., 2001; Cunningham, 2007; Cunningham et al., 2003a, 2003b; Devyatkin, 1974; Jolivet et al., 2007; Owen et al., 1999). However, the exact age of these surfaces is still largely debated. To the west, in Kazakhstan, the summit of the Karatau ridge was described by Allen et al. (2001) as remains of a Late Cenozoic dissected peneplain, without age argument. In Kyrgyzstan, Burbank et al. (1999) described a tilted planation surface on the northern flank of the Xrebet Kara Too range, overlaid by late Oligocene–Miocene sediments of the Shamshi Formation deposited without angular unconformity respectively to the erosion surface. The authors indicated that the basement had been largely flattened after the early Mesozoic. However, the oldest sediments exposed on some of the Kyrgyz planation surfaces belong to the poorly dated Late Cretaceous–Miocene Kokturpak group. These are generally considered as derived from deep weathering of the planation surface (Abdrakhmatov et al., 2001). Finally, based on thermochronology data, De Grave et al. (2011) dated the formation of the Song-Kul plateau flat morphology to the Middle Jurassic. Further east, in the eastern Chinese Tian Shan, Cunningham et al. (2003a) described the tilted surface of the Karlik Tagh and Barkol Tagh ranges as remnants of a Late Cretaceous–Early Cenozoic peneplain, without direct age constrain. On the same surface, Gillespie et al. (2017) obtained apatite fission track ages ranging between Late Jurassic and early Late Cretaceous and suggested that an initial surface formed during the Jurassic, was reworked during the Late Cretaceous and finally tilted during the Cenozoic. A similar scenario has been proposed for the tilted surface forming the southern slope of the Chinese north Tian Shan range (Dumitru et al., 2001; Jolivet et al., 2010).

Consequently, the age and unicity of these surface fragments are still debated. Yet, their detailed topography, as well as the facies, depositional environments and fossil content of the overlying Cenozoic sediments, represent key insights into the Late Mesozoic–Early Cenozoic topography of the region.

3.2. Key examples of pre-Cenozoic topographic features in the northern Chinese Tian Shan

Several large-scale fragments of planation surfaces are exposed in the Chinese northern Tian Shan. Some of them display paleo-valleys, carved into the erosion surface and filled with Cenozoic sediments. Immediately south of Kuitun City, a large paleo-valley is perched within the range, perpendicular and poorly connected to the present-day Kuitun River valley (Figs. 2 and 3). This paleo-valley is filled with a succession of (1) red alluvial sandstones, (2) grey lacustrine siltstones and sandstones, and (3) red, generally coarser alluvial sandstones and conglomerates (Fig. 4). The whole sequence is marked as E_3 (Oligocene) on the local geological map (XBGMR, 1973a, 1973b). However, the lacustrine sediments yielded ray scales and micro-fossil shells such as ostracods (*Ilyocypris* sp.), remains of bivalves (*Mytilopsis*? sp.), and especially gastropods (*Bithynia* sp.) that suggest a younger age (Fig. 4). Indeed, similar fossil assemblages are typical for the late early Miocene of the western Paratethys and can also appear in early middle Miocene strata (Reichenbacher et al., 2013; Pippèrr and Reichenbacher, 2017). Given their fossil content, we attributed a Burdigalian age to the grey lacustrine siltstone and sandstone deposits. Those sediments are therefore contemporaneous to the maximum lacustrine flooding represented by the Taxhi He Formation in the Junggar Basin (Charreau et al., 2009; Ji et al., 2008; Sun and Zhang, 2008, 2009). At that time, the lacustrine system documented in the Kuitun catchment and in the Junggar Basin had to be at a similar elevation with an opened connection to explain the occurrence of such a lacustrine fauna in the paleo-valley sediments. Owing to the Neogene uplift of the range (Avouac et al., 1993; Hendrix et al., 1994; Dumitru et al., 2001), these deposits are now perched at an elevation ranging from 2000 to 3000 m within the mountains, in a paleo-valley only connected

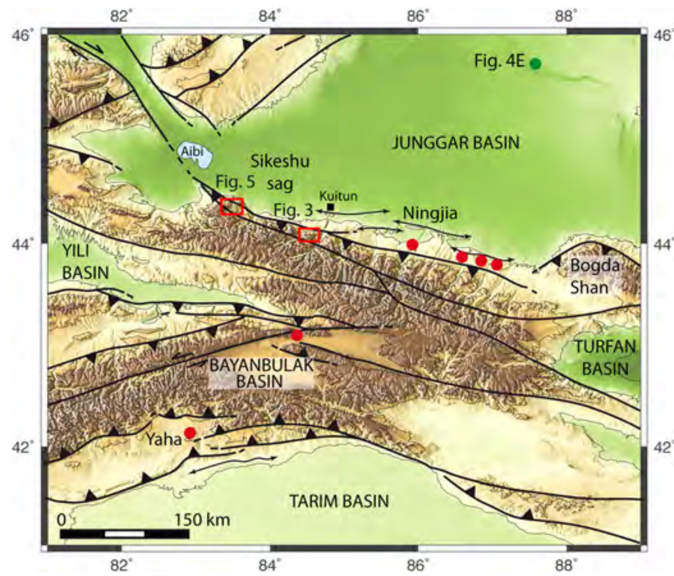

Fig. 2. Topographic and structural map of the Chinese Tian Shan area. The red boxes correspond to the fragments of Late Mesozoic topography described in Figs. 3 and 5. The red dots indicate the position of identified Palaeogene calcareous paleosols (see Fig. 7 for illustration). The green point indicates the sampling site of the Upper Cretaceous Trigonioididae bivalves illustrated in Fig. 4E.

to the Junggar Basin through the deeply incised canyon of the present-day Kuitun River.

Along the southern edge of the Kuitun paleo-valley, the sediments are conformably deposited on the Mesozoic erosion surface, now tilted towards the north and affected by an active left-lateral strike-slip fault (Fig. 3). To the north, the sedimentary series onlap on a much steeper slope without evidence of a preserved planation surface, nor of tectonic contact (Fig. 3). The relief between the mountain ridges surrounding the northern side of the valley and its paleo-thalweg is of the order of 1000 m, locally up to 1500 m. All this evidence demonstrates the existence of a significant relief along the northern edge of the Tian Shan during the late Oligocene–early Miocene, with incised valleys at the same elevation as and connected to the Junggar Basin. In the Kuitun River catchment area, the geometric relation between those topographic highs and the Mesozoic erosion surface is unclear although they seem to stand above that surface.

To the west, about 60 km south-east of Lake Aibi, another similar paleo-valley, the Tian Tai valley, is also preserved, incised into a ca. 300 km^2 plateau-like remnant of the Mesozoic planation surface (Figs. 2 and 5). This paleo-valley is filled with grey and red coarse alluvial sandstones and conglomerates overlain by grey lacustrine shale and siltstone layers (Fig. 6). Those series are marked on the geological maps as N_2d (Langhian to Tortonian Dushanzi Formation) (XBGMR, 1971) or N_1t (Burdigalian Taxi He Formation) (CGS, 2003). Like in the sediments preserved in the Kuitun River paleo-affluent, these lacustrine deposits contain ray scales and we thus favour the hypothesis that these sediments belong to the Taxi He Formation. Therefore, a connection between the Burdigalian lacustrine systems in the Tian Tai paleo-valley and in the Junggar Basin could have existed, like for the Kuitun. This initial connection has then been lost and replaced by a series of deep river canyons connected to the basin and strongly incising the paleo-valley and the surrounding Mesozoic planation surface (Figs. 2, 5 and 6).

This erosive surface, cut in a basement made of Carboniferous volcano-sedimentary rocks is multi-phased. It shows two subsurfaces separated by a ca. 100 m high riser and both cut by the Tian Tai paleo-valley (Figs. 5 and 6). The northern side of the latter is possibly limited by a tectonic structure, although no evidence of displacement was observed. The occurrence of basement highs

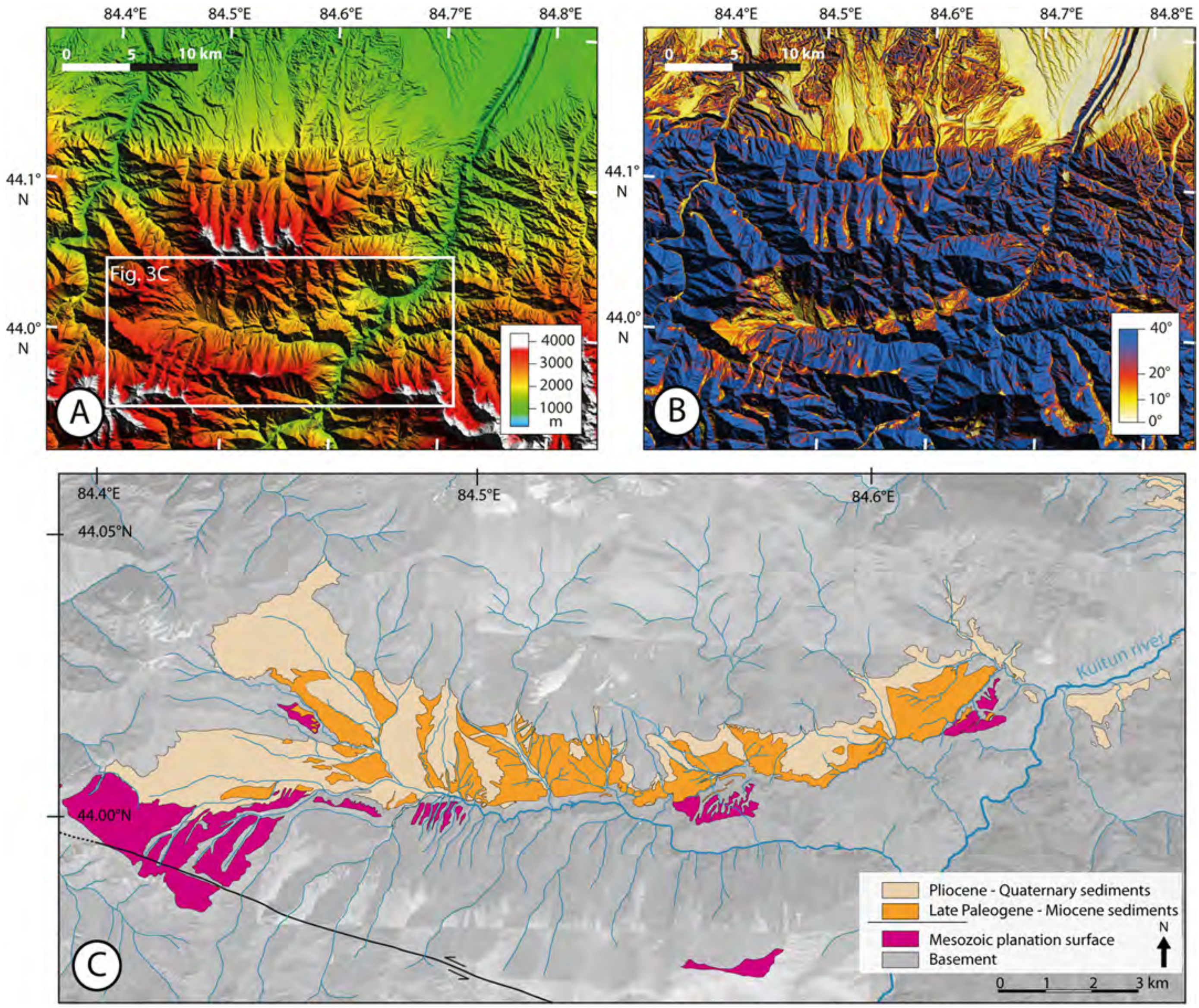

Fig. 3. Topography and geology of the paleo-valley in the Kuitun River catchment. (A) SRTM-derived DEM of the lower Kuitun River system. The white box corresponds to the paleo-valley mapped in Fig. 3C. (B) SRTM-derived slope map showing the steep relief of the range (blue colours) and the smoother relief of the sediment infill in the paleo-valley (yellow colours). (C) Geological map of the paleo-valley established from field work and satellite images (Google Earth).

cropping out within the sediments allows constraining the incision to about 100 m in the observed upper part of the paleo-valley. At the edges of the valley and around the basement highs, coarser, angular, proximal conglomerates seem to prevail, while the deposits are finer-grained in the valley centre. This suggests a local source for the sedimentary series, consistent with a small-scale valley shortly connected upstream.

4. Late Cretaceous–Early Cenozoic paleosols

In the basins surrounding the Tian Shan Range, the Cretaceous–Palaeogene transition is largely characterised by the occurrence of calcrete layers, some of them several metres thick (Fig. 7) (Heilbronn et al., 2015). Calcrete forms mainly through interaction between meteoric and/or groundwater and sedimentary rocks under seasonal semi-arid climate conditions in continental environments (Cerling, 1984; Dixon and McLaren, 2009; Retallack, 1997). Pedogenic calcification may be associated to biological activity, mainly to water exchanges between soil and plant roots or non-biogenic precipitation of carbonate due to seasonal variations in the water content of the soil (Dixon and McLaren, 2009). Generally, both mechanisms are acting together to develop the calcrete through local leaching of the host rock and re-precipitation of elements in combination with atmospheric CO_2 (Cerling, 1984; Dixon and McLaren, 2009). Their development further requires a near absence of erosion or sedimentation during several hundred thousand to millions of years (Ludwig and Paces, 2002; Retallack, 1997). The occurrence of calcrete in a sedimentary series is thus indicative of both a seasonal semi-arid climate and an absence of important erosion or sedimentation (i.e. of local relief degrading or basin subsidence).

In the southern Tian Shan foothills towards the Tarim Basin, along the Yaha River section (Fig. 2), the upper part of the Late Cretaceous Bashijiqike Formation is marked by an increasing occurrence of decimetre thick calcareous paleosols, the last ca. 15 m being formed by a massive hardpan calcrete developed in coarse sandstone and conglomerate sediments (Fig. 7A and B). The Oligocene Kumugeliemu Formation then overlies this massive calcrete without evidence of angular unconformity. However, a huge discrepancy in age between the deposits below and

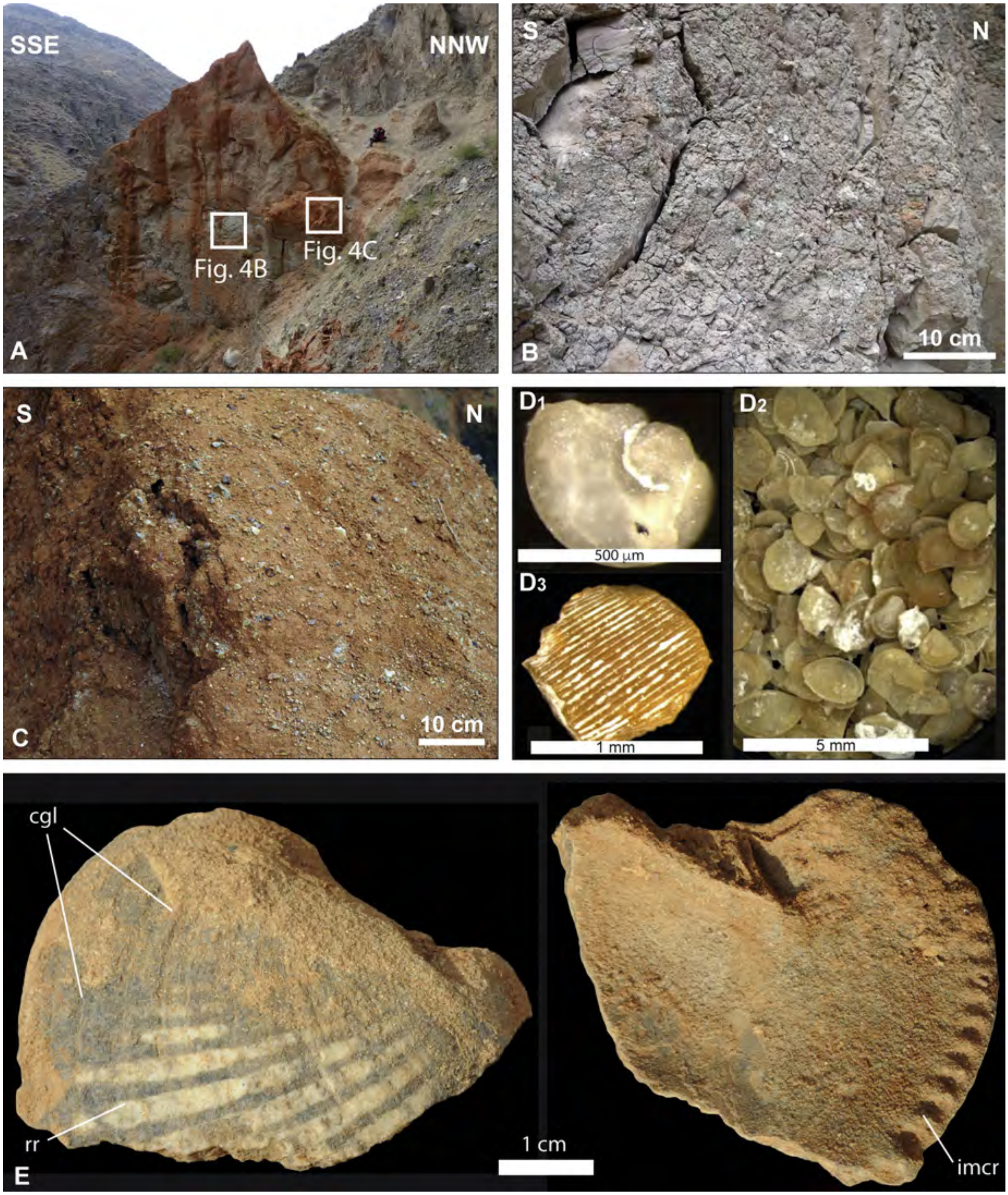

Fig. 4. Field pictures of the sediment infill of the paleo-valley in the Kuitun River catchment area. (A) Remnants of the Cenozoic sediments at the eastern end of the paleo-valley. (B) Detail of the grey Burdigalian lacustrine deposits. (C) Detail of the red alluvial deposits. (D) Remains of *Bithynia* sp. Gasterops (shell – D_1 – and opercula – D_2) and ray scales (D_3) found in the grey lacustrine sediments. (E) Fragments of *Pseudohyria* ex gr. *gobiensis* or *Pseudohyria* ex gr. *sinkiangensis* bivalves collected from the Upper Cretaceous series of the central Junggar Basin (see Fig. 2 for sample location). Note the thick shell and the occurrence of strong radial ribs (rr), internal marginal crenulation (imcr) and commarginal growth lines (cgl) (Sha, 2007, 2009). The orientation of Figs. 4B and 4C is indicative.

above this calcrete has been evidenced from independent magnetostratigraphic studies. Peng et al. (2006) obtained an age of ∼65.6 Ma at the base of the calcrete layer while Huang et al. (2006) calculated an age of ∼32 Ma for a thick conglomerate layer, a few metres above the base of the Kumugeliemu Formation (see correlation of the dated sections in Wang et al., 2009) (Fig. 7A). Given that the development of such a thick calcrete layer should span several million years (Ludwig and Paces, 2002; Retallack, 1997), we propose that the time gap of ca. 34 million years observed in the magnetostratigraphy data between the base of the Kumugeliemu Formation and the top of the Bashijiqike Formation is represented by the outstanding thick calcrete layer that separates those two formations. Erosion hiatus cannot be excluded inside the sediment forming the calcareous paleosol but the calcrete undoubtedly marks an extreme time condensation.

Although their exact age and time-span are not as constrained as in the Yaha River section, similar major pedogenic calcrete layers can be observed in other basins around and within the range. To the west, in the Fergana Basin, De Pelsmaeker et al. (2018) report numerous calcareous paleosols in Late Cretaceous–Palaeogene

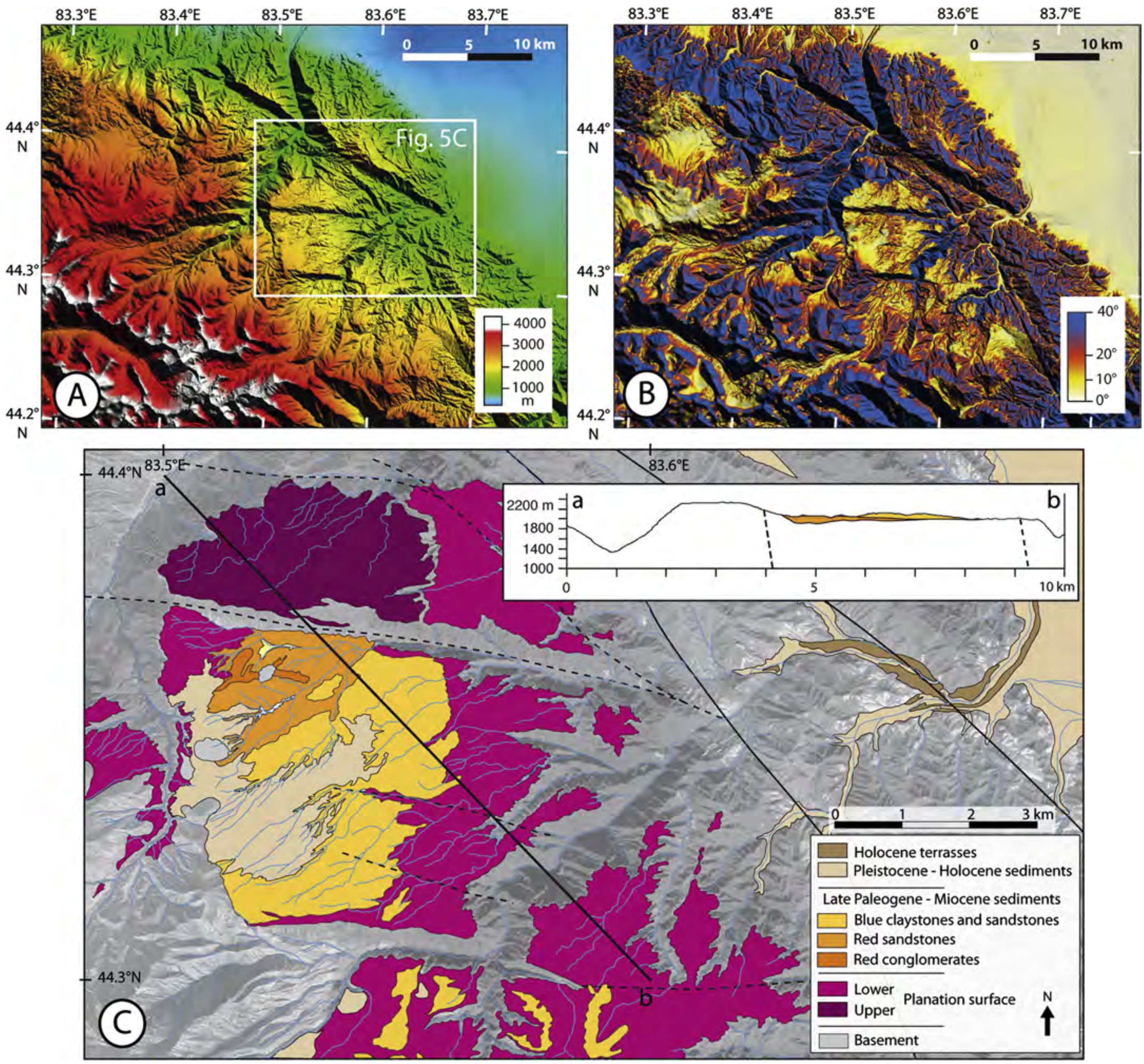

Fig. 5. Topography and geology of the Tian Tai paleo-valley. (A) SRTM-derived DEM of the Tian Tai area. The white box corresponds to the paleo-valley and associated plateau surface mapped in Fig. 5C. (B) SRTM-derived slope map showing the steep relief of the range (blue colours) and the smoother relief of the planation surface (yellow colours). Note the deep active canyons incising the Mesozoic surface. (C) Geological map of the Tian Tai paleo-valley and flattened basement established from field work and satellite images (Google Earth). The schematic cross-section a–b shows that the paleo-valley is only a few 100 m deep. The white squares indicate the position of the pictures shown in Fig. 6.

deposits. In the Bayanbulak Basin (Figs. 2, 7C and 7D), Heilbronn et al. (2015) describe a several metres thick hardpan calcrete that they attribute to the Cretaceous–Cenozoic transition. To the east, in the Turfan Basin (Fig. 2), a Late Cretaceous–Early Cenozoic major calcrete also occurs between the uppermost Late Cretaceous Subashi Formation and the late Palaeocene Taizicun Formation (Mateer and Chen, 1992).

Finally, in the southern Junggar Basin (Fig. 2), thick pedogenic calcrete layers developed in conglomerates are exposed too. They are interpreted as the top layers of the Late Cretaceous Donggou Formation (Hendrix et al., 1992) and overlain, without angular unconformity, by the poorly dated Palaeocene–early Miocene Ziniquanzi Formation. In the Ningjia River section, this calcrete is, like on the Yaha River section a massive 8 to 10 m thick hardpan (Heilbronn et al., 2015; Hendrix et al., 1992) (Fig. 7E and 7F). Further west, in the Sikeshu Sag (Fig. 2), Gao et al. (2013) described a Late Cretaceous–pre-Palaeogene unconformity underlined by a ca. 30 m thick weathering crust. We interpret this as a possible lateral stratigraphic near-equivalent of the pedogenic carbonate layers developed in a slightly different, more humid environment. Although no magnetostratigraphic data are available for the Cretaceous and Lower Cenozoic series of the southern Junggar Basin, we suggest that, like in the northern Tarim, the calcrete layers observed along the northern piedmont of the Tian Shan Range could represent a significant time interval of several million years.

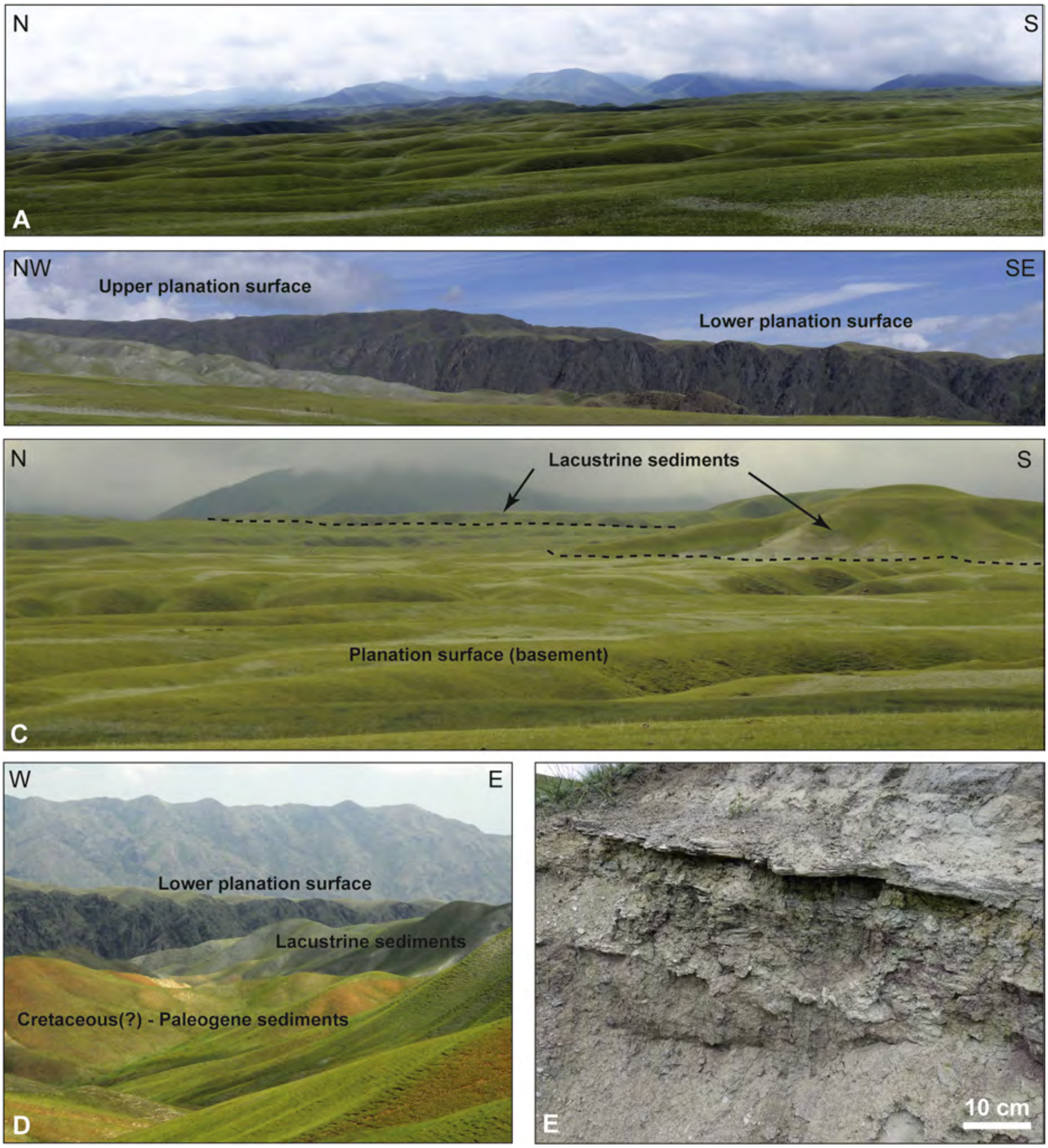

Fig. 6. Field pictures of the Tian Tai area (see location of each picture in Fig. 5). (A) General view of the Mesozoic planation surface. (B) View of the two steps of this erosion surface observed on the northern side of the study area (see Fig. 6). No fault has been observed along the scarp suggesting that these two sub-surfaces correspond to different erosion events rather than being tectonically offset. (C) View of the grey lacustrine sediments deposited on the planation surface. (D) Remnants of the Cenozoic sediment filling in the paleo-valley (foreground) incised into the two levels of the Mesozoic erosive surface (background). (E) Detail of the grey lacustrine deposits.

5. Implications for the topographic, tectonic and climatic evolution of the Tian Shan Region

5.1. Cretaceous–Palaeogene topography and calcrete development

As reported above, the occurrence of Late Cretaceous–Palaeogene paleo-valleys incised in extensive flat erosion surfaces surrounded by topographic ridges, suggest that the Late Cretaceous–Palaeogene topography of the northern Chinese Tian Shan included several hundred metres to one-and-a-half kilometre-high reliefs overlooking large plains formed by multi-phased nested Mesozoic erosive surfaces (Fig. 8A).

The incision period of the paleo-valleys in this paleo-topography is then comprised between the Mesozoic formation of the planation surface – considered as largely initiated during the Jurassic (Bullen et al., 2001; Dumitru et al., 2001; Jolivet, 2015) and rejuvenated during the Late Cretaceous–Early Cenozoic (Cunningham et al., 2003a; Gillespie et al., 2017) – and their sediment filling during late Oligocene–early Miocene. During the Palaeogene, the conglomeratic nature of the calcrete-supporting sediments in the surrounding basins testifies to nearby reliefs that eroded immediately prior to the calcite impregnation. However, the formation of calcrete layers also suggests an absence of strong contemporaneous relief degrading or basin subsidence. Accordingly, the paleo-valleys most probably formed during the Cretaceous, possibly during a phase of local tectonic reactivation of inherited structures driven by far-field effects of large geodynamic processes affecting the Central Asian lithosphere (e.g. the Lhasa block collision or the

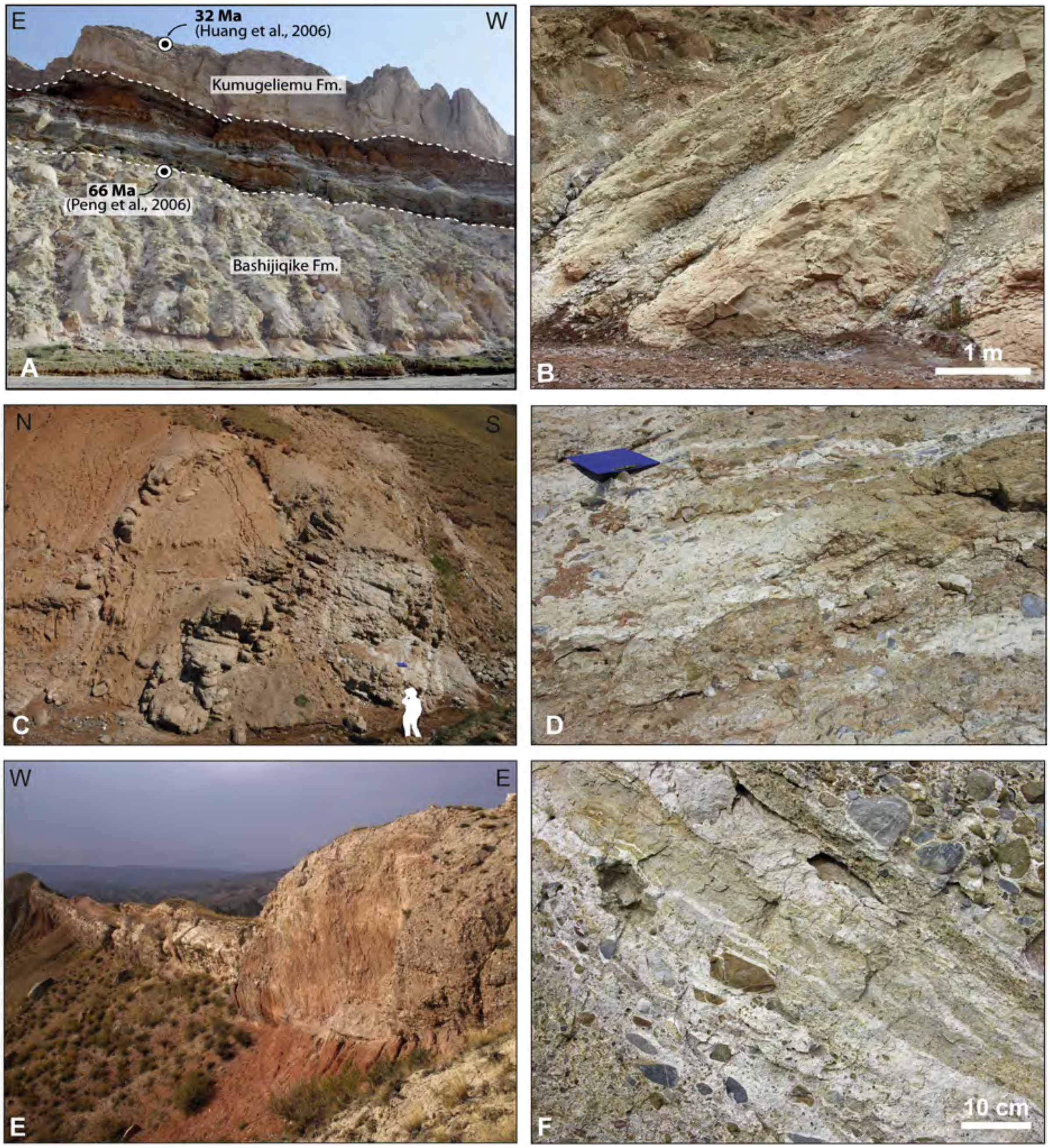

Fig. 7. Field pictures of the calcrete. (A) General and (B) detailed views of the Yaha calcrete in the southern Tian Shan. Magnetostratigraphic ages are reported in Fig. 7A, showing the huge time period included in the calcrete layer (C) general and (D) detail views of the Bayanbulak calcrete in the central Tian Shan (E) general and (F) detail views of the Ningjia River calcrete in northern Tian Shan. See Fig. 2 for the location of the Yaha, Bayanbulak and Ningjia sections.

closure of the Mongol–Okhotsk Ocean), as it has already been documented elsewhere in the Tian Shan area (De Grave et al., 2007; Dumitru et al., 2001; Glorie et al., 2010; Hendrix et al., 1992; Jolivet et al., 2010; De Pelsmaeker et al., 2018). By late Upper Cretaceous–Palaeocene, tectonic activity mostly ceased within Central Asia, except for very localised uplift along some major strike-slip faults (Jolivet et al., 2010; Bosboom et al., 2017; De Pelsmaeker et al., 2018). This near absence of relief building associated to the long-term semi-arid climate (see below) enhanced the formation of thick calcrete layers such as those observed in the Yaha and south Junggar sections.

In terms of climate, several authors suggested that the proto-Paratethys Sea might have brought humidity to Central Asia during the Late Cretaceous and Early Palaeogene (Ramstein et al., 1997; Zhang et al., 2007) (Fig. 1). Bosboom et al. (2014, 2017) established a link between the progressive retreat of the proto-Paratethys Sea and the stepwise middle to late Eocene Asian aridification evidenced in the Xining Basin (Eastern Tibet) (Dupont-Nivet et al., 2007). On the contrary, the widespread occurrence of calcrete layers around and within the Tian Shan Range during the Late Cretaceous–Palaeogene indicates a persistent semi-arid climate in the area at the Mesozoic–Cenozoic boundary (De Pelsmaeker et al., 2018; Heilbronn et al., 2015; Hendrix et al., 1992; Mateer and Chen, 1992). In addition, Heilbronn et al. (2015) showed that the δ^{18}O values obtained from these Late Cretaceous–Palaeogene calcretes are very homogeneous through time and space suggesting a limited climate change during that period. A similar long-term semi-arid climate has been inferred by Licht et al. (2016) from the aeolian record on the loess plateau since 42 Ma. In other words,

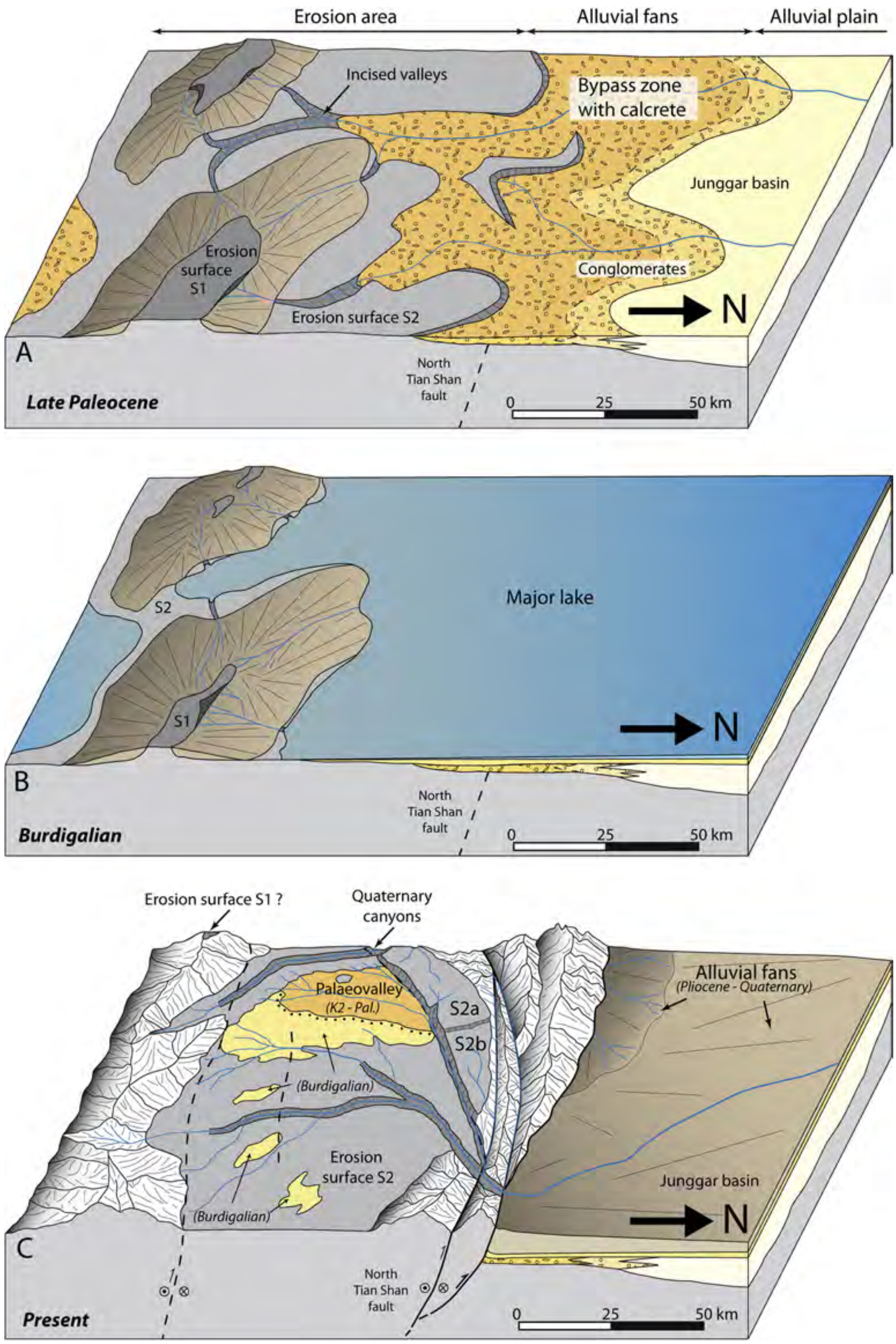

Fig. 8. Topographic evolution of the northern Tian Shan between the Late Palaeocene and present-day. (A) During the Late Cretaceous–Palaeocene, valleys were incised into the Mesozoic planation surface. A bypass zone developed along the southern margin of the Junggar basin leading to the formation of thick calcrete layers. (B) During the early Miocene, a large lake system developed, flooding the southern Junggar basin as well as the Late Cretaceous–Palaeogene valleys. (C) Due to the Miocene to Quaternary tectonic reactivation of the range, the paleo-valleys were disconnected from the Junggar basin and are preserved on plateau-like surfaces perched into the northern Tian Shan range. See Section 5 for discussion.

the aridity rather seems to pre-date the final withdrawal of the proto-Paratethys Sea.

5.2. Late Palaeogene–early Neogene evolution

By the late Eocene–early Oligocene, the condensed sedimentation marked by thick the calcrete layers ceased although the climate remained largely semi-arid (Sun and Zhang, 2008; Heilbronn et al., 2015), which indicates an enhanced subsidence in the basins associated with renewed deformation in the Tian Shan. This is consistent with previous studies suggesting that Cenozoic deformation along the southern front of the Tian Shan initiated during late Eocene–Oligocene (Allen et al., 1994; Jia et al., 2015). The final regression of the proto-Paratethys Sea at ∼36.7 Ma was contemporaneous of this onset of the Cenozoic deformation in the range (Bosboom et al., 2014, 2017) (Fig. 1). Since this last regression preceded the large sea-level drop associated with the Eocene–Oligocene Transition (EOT) at ~34 Ma (Dupont-Nivet et al., 2007), it is attributed by Bosboom et al. (2014, 2017) to the onset of tectonic uplift in the Pamir and Kunlun ranges. We suggest that the incipient uplift in the Tian Shan at that time may have also participated to this final sea retreat from the Tarim Basin.

However, the uplift of the range remained very limited up to the Miocene since thermochronology analyses indicate that basement exhumation initiated in the Tian Shan only around 25 Ma (Dumitru et al., 2001; Sobel et al., 2006; Yang et al., 2015), at a very slow rate of less than 0.1 mm/year that prevailed up to 16 Ma (Macaulay et al., 2014). Moreover, at least to the north, the Kuitun affluent and Tian Tai paleo-valleys contain sediments of an open lacustrine system indicating that the large lake that existed in the southern Junggar Basin during the early Miocene (Charreau et al., 2009, 2012) also flooded these valleys in the range (Fig. 8B). This implies a very low uplift, a limited income of clastic material and an absence of a well-developed piedmont at that time, at least in the northwestern part of the Chinese Tian Shan.

The discovery of ray scales in the Burdigalian lake sediments also suggests that during this period the Junggar Basin was possibly connected through a river system, to a marine environment, most probably the proto-Paratethys Sea to the west. Present-day freshwater rays such as Potamotrygonidae or Dasyatidae have evolved from marine ancestors and live only in river systems connected to the marine environment (Berra, 2001; Lovejoy et al., 2006). Therefore, fluvial systems connecting the Junggar to the Alakol–Balkash system and then to the sea further west could have existed, as well as a possible connection to the Turgay Straight through the paleo-Irtysh river (Fig. 1). Similar connections to a marine environment are also suggested by the occurrence of *Pseudohyria* Trigonioididae bivalves in the Upper Cretaceous series (Donggou Formation, XBGMR, 1973b) of the central Junggar Basin (Fig. 4E). Although the fossils are incomplete, we identified them as *Pseudohyria* ex gr. *gobiensis* or *Pseudohyria* ex gr. *sinkiangensis* (Sha, 2007, 2009). The species *Pseudohyria gobiensis* has been described in southern Mongolia in the Late Cretaceous Bayn Shire and Iren Dabasu formations, together with a vertebrate assemblage including hybodont sharks, rays and plesiosaurs, here also suggesting a connection to a marine environment through a fluvial system (Morris, 1936; Currie and Eberth, 1993). This should be verified but if such a connection, even episodical, existed during the Late Cretaceous to early Miocene between the Junggar Basin and the sea, it would challenge the commonly accepted long-lasting endorheic setting of this basin (Carroll et al., 2010; Bian et al., 2010).

The Early Miocene lacustrine deposits in the northern Tian Shan paleo-valleys are now located at an elevation of around 2000 m a.s.l., whereas the Taxi He Formation, which corresponds to the time-equivalent lacustrine deposits in the Junggar Basin (Charreau et al., 2009; Ji et al., 2008; Sun and Zhang, 2008, 2009) lies 2000–3000 m b.s.l. in the range foothills (Burchfiel et al., 1999; Guan et al., 2009; Li et al., 2011) (Fig. 8C). The post-early Miocene deformation of the northern Tian Shan has thus produced 4000–5000 m of differential vertical movement between the uplifted range and its subsiding proximal foreland. However, without knowing the initial elevation of the Taxi He lacustrine deposits a.s.l., it is difficult to conclude about the respective amount of uplift and subsidence through this orogenic system.

6. Conclusions

Based on the observations presented in this work, we argue that the pre-Oligocene Tian Shan already had a structured topography including several hundred metres to one-and-a-half kilometre high reliefs overlooking a multi-phased Mesozoic planation surface incised by paleo-valleys at the northern edge of the range. The paleo-valleys most probably formed during the Late Cretaceous–early Palaeogene, possibly during a phase of local tectonic reactivation of inherited structures driven by far-field effects of the Lhasa block collision or the closure of the Mongol–Okhotsk Ocean. During the Palaeogene, the Tian Shan paleo-topography was then associated with very low subsidence rates in the surrounding basins and a near absence of uplift in the range.

By late Eocene–early Oligocene, an enhanced subsidence in the basins associated with the probable onset of the Cenozoic deformation in the range is contemporaneous with the final retreat of the proto-Paratethys Sea from the Tarim Basin. This suggests that the incipient uplift in the Tian Shan may have participated, together with the growth of the Pamir and Western Kunlun ranges, to this regression. In terms of climate however, there is no obvious relationship between an aridity enhancement in Central Asia and this retreat of the proto-Paratethys Sea, a semi-arid climate prevailing at least since the Late Cretaceous in the studied area.

While the onset of the Cenozoic deformation in the Tian Shan seems to be early Oligocene, uplift must have stayed limited at least up to the early Miocene, since paleo-valleys to the north of the range could be flooded by the lacustrine system developed in the Junggar Basin at that time. Fossils assemblages, including particular bivalves in Upper Cretaceous deposits and ray scales in the sediments of this lacustrine system, suggest that up to this period, the Junggar Basin was possibly connected, even episodically, through a river system to a marine environment, challenging the commonly accepted long-lasting endorheic setting of the Junggar Basin.

Finally, the post-early Miocene relative vertical motion between this subsiding basin and the uplifted range can be estimated to 4000 to 5000 m. However, the initial elevation a.s.l. of the lower Miocene lacustrine deposits is still lacking to conclude about the respective amount of uplift and subsidence through the orogenic system.

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