Late Eocene palaeogeography of the proto-Paratethys Sea in Central Asia (NW China, southern Kyrgyzstan and SW Tajikistan)

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Abstract: The Cretaceous and Palaeogene sediments of the basins in Central Asia include the remnants of the easternmost extent of a vast shallow epicontinental sea, which extended across the Eurasian continent before it retreated westwards and eventually isolated as the Paratethys Sea. To improve understanding of its long-term palaeogeographical evolution, we complement the well-constrained chronological framework of the Tarim Basin in China with stratigraphic records of the sea retreat from the Fergana Basin and the Alai Valley Basin in southern Kyrgyzstan and the Afghan–Tajik Basin in SW Tajikistan. By lithostratigraphic analyses and identification of bivalve assemblages, this study establishes for the first time a clear and detailed regional correlation of Palaeogene marine strata across Central Asia, showing that the basins share a similar palaeogeographical evolution characterized by a long-term stepwise retreat punctuated by short-term shallow-marine incursions. Our correlation shows that the last two marine incursions recognized in the Tarim Basin can be traced westwards. The permanent disappearance of the sea from Central Asia probably occurred with limited diachroneity in the late Eocene, before the isolation of the Paratethys Sea, shifting the easternmost margin of the sea hundreds of kilometres westwards and probably significantly reducing moisture supply to the Asian interior.
it may have served as an important moisture source for the Asian interior (Ramstein et al. 1997; Zhang et al. 2007).

This sea was initially connected to the western Tethys before it retreated and, ultimately, separated into the Paratethys Sea ( Báldi 1984; Rusu 1985; Dercourt et al. 1993; Robinson et al. 1996; Rögl 1999; Popov et al. 2004; Schulz et al. 2005; Vincent et al. 2005; Allen & Armstrong 2008; Bosboom et al. 2011). We therefore refer to it as the proto-Paratethys Sea, although it is often named the Tajik Sea, Turan Sea or Tarim Sea (e.g. Tang et al. 1992; Burtman & Molnar 1993). It supposedly entered Central Asia from the west in the Early Cretaceous and retreated westwards after five marine incursions (Tang et al. 1989; Burtman & Molnar 1993; Lan & Wei 1995; Burtman 2000). Our previous biomagnetostratigraphic study has accurately dated the last two incursions into the Tarim Basin, showing that the retreat of the sea occurred stepwise and mainly in the late Eocene (Bosboom et al. 2011, 2014b, c). In order to evaluate the timing and palaeogeography of the long-term stepwise sea retreat from Central Asia, this study aims to correlate the poorly dated Palaeogene marine records further west in the Alai Valley Basin and the Fergana Basin, Alai Valley Basin, Tarim Basin and Xining Basin are shown on the inset (present-day coastal outline obtained from GPlates 0.9.7.1).

**Fig. 1.** Satellite map of Central Asia showing the locations of the studied lithostratigraphic sections and the present-day extent and age of the marine sediments associated with the fourth and last fifth transgressions, based on data of this study and Bosboom et al. (2011, 2014b, c). The digital elevation data was downloaded from the online database of the CGIAR Consortium for Spatial Information (Jarvis et al. 2008). The locations of the Afghan–Tajik Basin, Fergana Basin, Alai Valley Basin, Tarim Basin and Xining Basin are shown on the inset (present-day coastal outline obtained from GPlates 0.9.7.1).

**Geological setting**

**Tectonism**

The study area in southern Kyrgyzstan and SW Tajikistan is bounded by the Pamir Mountains in the south and the Tien Shan Mountains in the north. These thrust belts were activated in response to the early Eocene Indo-Asia collision that occurred at around 50 Ma (e.g. Yin & Harrison 2000; van Hinsbergen et al. 2012; Tripathy-Lang...
Fig. 2. Simplified lithostratigraphic correlation of the Fergana and Afghan–Tajik basins with the chronological framework of the marine incursions recognized in the SW Tarim Basin based on results of this study. The shaded area highlights the formations corresponding to the fourth and fifth transgressions in the Tarim Basin, which have been accurately dated by integrated biomagnetostatigraphy (Bosboom et al. 2011, 2014b, c), allowing for temporal comparison with the palaeogeographical evolution of the proto-Paratethys Sea (e.g. Baldi 1984; Rusu 1985; Dercourt et al. 1993; Proust & Hosu 1996; Robinson et al. 1996; Rögl 1999; López-Blanco et al. 2000; Popov et al. 2004, 2008; Schulz et al. 2005; Vincent et al. 2005; Akhmetiev & Beniamovski 2006; Akhmetiev 2007; Lartaud 2007; Allen & Armstrong 2008; Johnson et al. 2009; Costa et al. 2010; Jakobleva & Heilmann-Clausen 2010; Dawber et al. 2011), the regional tectonic evolution of the Pamir, Kunlun Shan and Tien Shan (e.g. Hendrix et al. 2008; Johnson et al. 2009; Villa et al. 2009; Costa et al. 2010; Jakobleva & Heilmann-Clausen 2010; Dawber et al. 2011), and backstripping (Yang & Liu 2002; Amidon & Hynek 2010; Berkshaw et al. 2012; De Grave et al. 2012), thermochronological (Sobel & Dumitru 1997; Jolivet et al. 2001; Amidon & Hynek 2010; Sobel et al. 2013), palaeomagnetic (Thomas et al. 1994; Yin et al. 2002), and backstripping (Yang & Liu 2002) data. However, earlier uplift may have initiated some time in the middle Eocene but evidence is sparse and not well constrained (e.g. Jolivet et al. 2001; Yin et al. 2002; Amidon & Hynek 2010; Cowgill 2010).

The Pamir forms the western extension of the Tibetan Plateau. Here thrusting and exhumation occurred mostly in the late Oligocene–early Miocene at approximately 25–18 Ma, based on sedimentological (Burtman 2000; Yin et al. 2002), stable isotope and provenance (Bershaw et al. 2012), thermochronological (Sobel & Dumitru 1997; Jolivet et al. 2001; Amidon & Hynek 2010; Sobel et al. 2013), palaeomagnetic (Thomas et al. 1994; Yin et al. 2002), and backstripping (Yang & Liu 2002) data. However, earlier uplift may have initiated some time in the middle Eocene but evidence is sparse and not well constrained (e.g. Jolivet et al. 2001; Yin et al. 2002; Amidon & Hynek 2010; Cowgill 2010).

The intracontinental Tien Shan is a Palaeozoic accretionary orogen composed of multiple Proterozoic and Palaeozoic segments (e.g. De Grave
et al. 2012). Thermochronological dating in the Kashi Basin, the Tarim Basin and the Kyrgyz Alai Valley Basin indicates exhumation by reactivation of the Late Palaeozoic thrust structures in the Tien Shan that commenced near the Oligocene–Miocene boundary at approximately 24–22 Ma; southward propagation, however, did not reach the Kashi Basin-bounding thrust until about 19 Ma (Sobel & Dumitru 1997; Sobel et al. 2006; De Grave et al. 2012; Yang et al. 2014). Consequently, the molasse assemblages in Kyrgyzstan and Tajikistan eventually grade into coarse-grained sandstones and conglomerates with mudstone interbeds of Miocene age (Markowsky 1959; Pomazkov 1972; Coutand et al. 2002; Nikolaev 2002). These Neogene sediments have been weakly deformed by basinward thrusting and overloading of the Pamir and Tien Shan, which is estimated to have resulted in 300 km of total shortening (Burtman & Molnar 1993; Burtman 2000) and is ongoing up until today in response to the continuous northward movement of India into Eurasia.

This tectonic evolution had specific repercussions in the studied areas located in the Alai Valley Basin and Fergana Basin in Kyrgyzstan, and the Afghan–Tajik Basin in Tajikistan (Fig. 1). The east–west-trending Alai Valley is an intramontane basin between the Trans-Alai and Alai ranges that used to connect the present-day Afghan–Tajik and Tarim basins before the northward indentation of the Pamir and the reactivation of the southern Tien Shan after the early Eocene Indo-Asia collision (Molnar & Tapponnier 1975; Hendrix et al. 1992; Burtman & Molnar 1993; Burtman 2000).

The Fergana Basin spreads mostly across eastern Uzbekistan, and has been marginally overthrusted by the Chatkal Range in the north (along the North Fergana Fault) and the Alai Range in the south (along the South Fergana Fault) in response to the northward movement of India into Eurasia (Burtman & Molnar 1993; Burtman et al. 1996). Shortening in the Chatkal Range has been estimated to be 60–100 km (Thomas et al. 1993; Zubovich et al. 2010). The NE margin of the basin is bounded by the major Talas-Fergana dextral strike-slip fault (Burtman et al. 1996). The basin has been proposed to have formed in response to Permo-Triassic rifting of the Palaeozoic basement, and the overlying sedimentary infill comprises Permian–Early Triassic sedimentary volcanic rocks, Jurassic coals and Early Cretaceous continental deposits (Pomazkov 1972).

The Afghan–Tajik Basin spreads across eastern Uzbekistan, SW Tajikistan and NE Afghanistan, and has been marginally overthrusted by the Tien Shan in the north (Gissar Range) along the South Gissar Fault, by the Pamir in the east (e.g. the Darvaz, Trans-Alai and Peter the First ranges) along the major Darvaz Fault and by the Hindu Kush in the south along the Ishkashym Fault Zone (Brookfield & Hashmat 2001; Nikolaev 2002). In the west, the Afghan–Tajik Basin grades into the Amu-Darya Basin on the Turan Plate (Nikolaev 2002). Basin development has been proposed to have been initiated by Triassic rifting, and the sedimentary infill directly overlying the Palaeozoic basement comprises Lower–Middle Jurassic coal-bearing deposits of both marine and continental origin, Upper Jurassic carbonate and halokinetic salt deposits of marine origin, and Early Cretaceous continental red beds (Markowsky 1959; Brookfield & Hashmat 2001; Nikolaev 2002).

### Marine palaeogeography

Marine deposition in Central Asia initiated as the proto-Paratethys Sea invaded Central Asia through the Afghan–Tajik Basin in the Albanian (Burtman & Molnar 1993; Burtman et al. 1996; Burtman 2000; Brookfield & Hashmat 2001; Nikolaev 2002), reaching the Tarim Basin in the Late Cretaceous through the Alai Valley Basin (Tang et al. 1992; Burtman & Molnar 1993; Burtman 2000). Here five transgressions and regressions have been recognized, of which the third is considered the largest (Fig. 2) (Tang et al. 1989; Lan & Wei 1995; Burtman et al. 1996; Burtman 2000). The subtidal facies are characterized by shallow-marine carbonate-platform and tidal-flat deposits including light-coloured limestones and sandstones with typical fossil assemblages, whereas the supratidal and intertidal facies comprise lagoonal and tidal-flat deposits including massive gypsum beds and reddish-brown gypsiferous mudstones (Mao & Norris 1988; Tang et al. 1989, 1992). The last major retreat from the palaeodepocentre in the SW Tarim Basin occurred at the Lutetian–Bartonian boundary at approximately 41 Ma, according to integrated biomagnetostratigraphic dating of marine deposits from the fourth transgression (base C18r: Bosboom et al. 2011, 2014b). The fifth and last regression from the westernmost margin of the Tarim Basin has been assigned a latest Bartonian–early Priabonian age by biostratigraphic constraints (near top C17n.2n–base C16n.2n: Bosboom et al. 2014c). These sea-retreath steps are concomitant with significant aridification in the Asian interior (Bosboom et al. 2014a), East Asian monsoonal intensification (Quan et al. 2011), closure of the Turgai Strait in the late Lutetian (Akhmetiev & Beniamovski 2006; Akhmetiev 2007; Iakovleva & Heilmann-Clausen 2010) and various late Eocene regressions reported from European basins (e.g. Proust & Hosu 1996; López-Blanco et al. 2000; Lartaud 2007; Costa et al. 2010; Dawber et al. 2011).
disconformity around the Eocene–Oligocene Transition (EOT) near the palaeodeposcentre shows that the Tarim Basin remained hydrologically part of the Tethyan realm up to at least the Oligocene, and had not yet been disconnected from the Fergana and Afghan–Tajik basins to the west by the tectonic closure of the Alai Valley Basin (Bosboom et al. 2014b).

The last regression in Central Asia is poorly constrained to late Oligocene time (Markowsky 1959; Burtman et al. 1996; Burtman 2000). It is estimated that the complete marine sequence of Cretaceous–Palaeogene age in the Fergana Basin exceeds 2000 m. In the northern Alai Valley Basin, this same sequence reaches a thickness in excess of 1000 m (Burtman & Molnar 1993; Burtman 2000). In the Afghan–Tajik Basin, the marine succession is divided into two major marine sub-assemblages from the Albian to the Paleocene and from the Eocene to the Oligocene, which together exceed 3000 m thickness in the centre of the basin (Burtman & Molnar 1993; Burtman 2000; Nikolaev 2002). The overlying molasse assemblages in both Kyrgyzstan and Tajikistan generally comprise late Oligocene fine-grained continental deposits with gypsum intercalations (Markowsky 1959; Pomazkov 1972; Coutand et al. 2002; Nikolaev 2002).

**Lithostratigraphy**

Here we study the last two regional marine incursions recognized in several analysed sections throughout the Alai Valley Basin, the Fergana Basin and the Afghan–Tajik Basin by describing and interpreting the general lithostratigraphy and lithofacies. This, and the review of previous lithostratigraphic descriptions and correlations (Pomazkov 1972; Dzhalilov et al. 1982; Burtman 2000), allow us to make a first-order lithostratigraphic regional correlation across these basins, which can ultimately be linked to our previously established stratigraphic framework of the last two marine incursions in the Tarim Basin (Fig. 2) (Bosboom et al. 2011, 2014b, c). See Tables A1 & A2 in the Appendix for a comprehensive overview of the applied stratigraphic nomenclature, and the corresponding lithostratigraphic descriptions, thicknesses and age estimates by Pomazkov (1972) and Dzhalilov et al. (1982).

**Sampled sections**

In August 2011, five lithostratigraphic sections were studied in southern Kyrgyzstan to reconstruct the palaeogeographical development of the shallow epicontinental sea covering Central Asia in the Cretaceous and Palaeogene: the Northern Alai Valley Composite section (39.6° N, 72.4° E) along the Alai Range (Tien Shan); the parallel sections of Datka (39.9° N, 73.5° E) and Uch-Tobo (39.9° N, 73.4° E) in the Alai Range (Tien Shan) between the Alai Valley Basin and the Fergana Basin; and the Tash-Kumyr (41.3° N, 72.2° E) and Ala-Buka (41.4° N, 71.4° E) sections in the Chatkal Range (Tien Shan) along the northern margin of the Fergana Basin (Fig. 1). These sections are named after nearby villages or cities (except for the Northern Alai Valley Composite section) and are exposed along tributary streams of major rivers (except for the upper part of the Tash-Kumyr section, which is along the road from Tash-Kumyr to Jalal-Abad). These sections have been chosen for their subcontinuous exposure, lack of faulting and simple structures, with a homoclinal dip ranging from 25° to 65°. The Northern Alai Valley has been studied previously by Coutand et al. (2002) and Strecker et al. (2003), who focused, respectively, on late Cenozoic tectonic convergence and on active mountain front geomorphology. The Tash-Kumyr and Ala-Buka sections were part of the palaeomagnetic research by Thomas et al. (1993) on the general Cenozoic tectonic history of the Tien Shan.

In the Afghan–Tajik Basin, three lithostratigraphic sections covering Central Asia in the Cretaceous and Palaeogene were studied in October 2012: the Aksu section (38.1° N, 68.58° E) in the SW near the Uzbek border; the Childara–Shuldara section (38.80° N, 70.35° E) on the western margin of the Pamir Mountains; and the Kuhdara section (38.65° N, 68.88° E) near Dushanbe (Fig. 1). These sections are all named after nearby villages or cities and are exposed along tributary streams of major rivers. The strata are continuously exposed with a homoclinal dip ranging from 35° to 80°. The Aksu and Childara sections have been the focus of various palaeomagnetic studies (Bazhenov et al. 1978; Klootwijk 1979; Bazhenov & Burtman 1981; Thomas et al. 1994) directed at the general Cenozoic tectonic history of the Tien Shan and Pamir.

The studied lithostratigraphic sections have been measured to decimetric precision (apart from poorly exposed intervals) and are shown in Figures 3 & 4. In general, the exposure is good, except in fine-grained less-resistant intervals (particularly in the Northern Alai Valley Composite section and the sections in the Afghan–Tajik Basin). The successions encompass an alternation of regressive and transgressive intervals (Fig. 5a). The regressive intervals are red-coloured oxidized successions comprising playa evaporites, pedogenic caliche beds, floodplain mudstones, and fluvial channel siltstones and sandstones with cross-bedding. The transgressive intervals are generally dominated by shallow-marine, light-coloured (bioturbated)
Fig. 4. Regional lithostratigraphic correlation across the Afghan–Tajik Basin in SW Tajikistan. See Figure 3 for an explanation.
Fig. 5. Field photographs of sections, formations and sedimentological features from the Alai Valley Basin, Fergana Basin and Afghan–Tajik Basin. (a) Overview of the Datka section in the Alai Valley Basin, clearly showing the third-order variations in sea level of the Palaeogene transgressions and regressions recognized in the Tarim Basin. At the top is the continental Massaget Formation. The overall stratigraphic thickness is approximately 1500 m. (b) Oyster packstone at the base of the Alai Formation in the Tash-Kumyr section in the Fergana Basin and (c) oyster samples collected from that bed (hammer used for scale). (d) Overview of the last fifth marine incursion recognized at the top of the Shuldara section in the Afghan–Tajik Basin. Stratigraphic thickness of the greenish coloured marine beds is approximately 200 m. (e) The gradual marine to continental transition of the last sea retreat as recorded in the Datka section. Deeper marine green mudstones are overlain by shallow carbonates, which grade into red floodplain mudstones with playa evaporite interbeds at the base and fluvial sandstone interbeds at the top. At the top are the red alluvial conglomerates of the Massaget Formation. (f) Fluvial fine-grained sandstone channels interbedded in red floodplain mudstones at the base of the Shurysay Formation in the Aksu section in the Afghan–Tajik Basin (person used for scale). (g) Cross-beded fluvial sandstones of the Shurysay Formation in the Datka section.
mudstones, marls, (oolithic) limestones and sandstones rich in oysters and other bivalves.

The lower and penultimate incursion

The transgressive surface at the base of the lower marine incursion is generally not well defined because of poor exposure but, in southern Kyrgyzstan, it is marked by a rather abrupt shift from oxidized clastics to non-oxidized calcareous deposits rich in shallow-marine fauna. In both the Fergana and Afghan–Tajik basins, the lithostratigraphy consists primarily of restricted shallow-marine deposits characterized by light-coloured (bioturbated) mudstones, marls and (oolithic) limestones and sandstones rich in fish teeth, oysters and other bivalves (Fig. 5b–c), which is very similar to that of the Kalatar and Wulagen formations of the fourth marine incursion recognized in the Tarim Basin (Bosboom et al. 2011, 2014). In the Fergana Basin and Alai Valley Basin, the end of this lower marine incursion is characterized by the rather abrupt transition into a relatively thin regressive interval of red-oxidized floodplain mudstones and fluvial fine-grained sandstone channels. The lithological characteristics of the deposits of this lower marine incursion are typical of the Alai and Turkestan formations in southern Kyrgyzstan (Pomazkov 1972). In the Afghan–Tajik Basin, this lower marine incursion consists of two transgression–regression sequences, which each range from open-marine subtidal to restricted lagoonal conditions and are separated by a clear unconformity (Fig. 4). This contact is characterized by incised oxidized tidal channels cutting into the restricted coastal marine sediments below at Aksu (at the 65 m level) and Shuldara (at the 2 m level in the upper part), and by a sequence of fine-grained mica sandstones directly overlying carbonate shoal oolitic grainstones at Kuhdara (at the 65 m level). An interval of red clays, siltstones and sandstones has been described previously from the Jukar Formation, and the general lithofacies of the two sequences are very typical of the Jukar, Beshkent and Lower Tochar formations of the Afghan–Tajik Basin (Dzhaliilov et al. 1982). The unconformity separating the two sequences has not yet been identified at the corresponding stratigraphic level in the studied sections in the SW Tarim Basin, which seemingly shows a more simple third-order variation in sea level (Bosboom et al. 2011, 2014b). The possibility that the two stacked, marine sequences in the Afghan–Tajik Basin correspond to the fourth and fifth marine incursions recognized in the SW Tarim Basin appears unlikely. The stacked marine sequences, capped by the playa evaporite beds of the Lower Tochar Formation in the Afghan–Tajik Basin, perfectly resemble the shallowing-upward trend associated with the fourth marine incursion in the Bashibulake Mine section at the westernmost margin of the Tarim Basin (Bosboom et al. 2014c). Hence, in the Alai Valley Basin, the Fergana Basin and the Afghan–Tajik Basin, the studied lower marine incursion correlates to the fourth marine incursion of the Tarim Basin (Bosboom et al. 2011, 2014b).

The upper and last incursion

The base of the upper marine incursion is only exposed in the Kyrgyz sections (the Fergana Basin and the Alai Valley Basin) and is, compared to the previous incursion, marked by a more gradual change from oxidized clastics to non-oxidized calcareous deposits rich in shallow-marine fauna. The marine sediments generally comprise red- and green-coloured (bioturbated) marls, and calcareous mudstones with occasional siltstone, sandstone and limestone interbeds rich in shells (Fig. 5d), which is characteristic of a restricted subtidal–intertidal and low-energy depositional environment. In the Afghan–Tajik Basin, it is generally poorly exposed and, at the Kuhdara section, it appears to be completely absent. In the Alai Valley Basin and Fergana Basin, the exposure is good but, owing to the downcutting of the conglomeratic Miocene Massaget Formation, the ensuing regression only seems to have been fully preserved in the Datka and Uch-Tobo sections. Here the marine sediments grade into playa evaporite beds and red-coloured fluvial floodplain mudstones and sandstones, typical of the Shurysay Formation (Fig. 5e–g). The observed green marly mudstone lithologies are characteristic of the marine Isfara, Hanabad and Sumsar formations in southern Kyrgyzstan (Pomazkov 1972) and the Kushan and Sanglak formations in the Afghan–Tajik Basin (Dzhaliilov et al. 1982), and correspond to the fine-grained marine members of the Bashibulake Formation of the fifth transgression that are restricted to the westernmost margin of the Tarim Basin (Bosboom et al. 2014c).

Synthesis

Our preliminary lithostratigraphic analyses indicate that the two last marine incursions can be correlated across Central Asia. The transgressive successions are thickest (reaching a total thickness of over 600 m) and best recorded in the Datka and Uch-Tobo sections in southern Kyrgyzstan (Fig. 3). As in the Tarim Basin, the gradual character of the two studied regressions is typical of shallowing-upward cycles (or cyclothems) recorded in shallow epicontinental seas (Aigner et al. 1990; Reading 2006). The same alternation of siliciclastic and carbonate deposits is observed, although clastic input is
generally higher than in the Tarim Basin. In southern Kyrgyzstan, medium- to coarse-grained sandstone beds rich in clastic pebbles are predominant throughout most sections, and the top of the lower incursion into the Afghan–Tajik Basin is characterized by frequent slumping, reworking, and micritic-rich siltstones and fine sandstones (Figs 3 & 4). The mixed depositional environment suggests that, superimposed on the overall shallowing-upward trend, high-frequency fluctuations in relative sea level, local climate and sediment supply result in lowstand/wet siliciclastic shedding and highstand/dry carbonate build-up (Budd & Harris 1990; Reading 2006).

Based on our findings, we correlated these last two marine incursions in the Alai Valley Basin, Fergana Basin and Afghan–Tajik Basin to the last two marine incursions recognized in the Tarim Basin, which have been accurately dated by integrated biomagnetostratigraphy (Bosboom et al. 2011, 2014b, c). This lithostratigraphic correlation with the fourth and fifth transgressions of the SW Tarim Basin is verified below by identification of collected bivalve specimens.

**Bivalve analyses**

The samples for bivalve analyses were collected from representative marine beds throughout the studied sections (Figs 3, 4, 6 & 7; Table 1) in order to verify our lithostratigraphic correlations, and to constrain the palaeogeography and palaeoenvironment of the stepwise sea retreat from Central Asia. All identified species are documented in Figure 6. Their distribution in the studied samples is indicated in Table 1. The correlations for the Alai Valley Basin and the Fergana Basin are partly based on studies from the Afghan–Tajik Basin, of which the formation names have been transferred to the stratigraphic scheme applied in southern Kyrgyzstan according to the stratigraphic scheme of Burtman (2000).

**Bivalves from the Alai Valley Basin and the Fergana Basin (southern Kyrgyzstan)**

**The Alai section.** Sample AL11-S03 yielded well-preserved specimens of *Sokolowia buhsii* (Grewingk 1853) (Fig. 6a: 6–8, 10), confirming the lithostratigraphic correlation with the Turkestan Formation (Vialov 1948). *Sokolowia buhsii* (Grewingk 1853) is typical of the Wulagen Formation, which records the fourth marine incursion into the SW Tarim Basin (Lan 1997) and has been accurately dated by integrated biomagnetostratigraphy as Lutetian (Bosboom et al. 2014b). It points to normal saline, warm and turbulent subtidal shallow-marine water conditions and shows extraordinary wide dispersal from the Tarim to the Transylvanian basins (Grewingk 1853; Vialov 1937; Berizzi Quarto di Palo 1970; Rusu et al. 2004). For a detailed review of the palaeoecological, stratigraphic and palaeogeographical significance of *Sokolowia buhsii* (Grewingk 1853) see Bosboom et al. (2011). From sample AL11-S02, only indeterminate gastropods with no biostratigraphic value were retrieved. Sample AL11-S01, taken 350 m below, revealed a bivalve assemblage of Upper Cenomanian age (Fig. 6a: 6–8).

**The Datka and Uch-Tobo sections.** Based on our lithostratigraphic correlation, the two samples UT11-S01 and UT11-S02 (Fig. 6a: 9; Fig. 6b: 9, 17, 18) would originate from the Alai–Turkestan formations, which is perfectly in line with the identification of *Sokolowia buhsii* (Grewingk 1853). The specimens from sample UT11-S02 somewhat reminiscent of *Ostrea (Turkostrea) cizancourtii* (Cox 1938), which is typical of the Alai Formation (Berizzi Quarto di Palo 1970). However, careful comparison of the 10 available specimens shows it is, in fact, a more slender and small-sized morphotype of *Sokolowia buhsii* (Grewingk 1853) reported from the Turkestan Formation of northern Afghanistan by Berizzi Quarto di Palo (1970). See the previous subsection on ‘The Alai section’ for its palaeoenvironmental significance and palaeogeographical distribution.

The specimens of sample UT11-B02 were collected from various shell beds at the base of the upper transgression, which has been lithostratigraphically correlated to the top of the Rishtan Formation and the base of the Isfara Formation. *Platygena asiatica* (Romanovskiy 1879) and *Ferganea ferganensis* (Romanovskiy 1879), found therein, represent index fossils of two different stratigraphic levels (e.g. Berizzi Quarto di Palo 1970). *Platygena asiatica* (Romanovskiy 1879) confirms correlation with the Rishtan Formation of the Fergana Basin (Vialov 1937; Berizzi Quarto di Palo 1970). Further east, *Platygena* is the index fossil of the Second and lowermost Third Member of the Bashibulake Formation (Lan 1997). This formation records the fifth marine incursion in the Tarim Basin, and has been biostratigraphically constrained in age between the latest Bartonian and early Priabonian (Bosboom et al. 2014c). *Platygena asiatica* (Romanovskiy 1879) appears to have a wide distribution based on reports from Eocene strata of Libya in North Africa (Cox 1962). This species produces remarkable thick shells with sizes of up to 15 cm and was probably a sediment relocator on sandy bottoms in fully marine, shallow subtidal–lower intertidal environments (Lan 1997). However, in the Fergana Basin, *Ferganea ferganensis*...
(Romanovskiy 1879) has previously only been reported from the Sumsar Formation (Salibaev 1972). In the SW Tarim Basin, it also shows a distinctly different stratigraphic distribution from Platygena asiatica (Romanovskiy 1879), marking the uppermost Third and Fourth Members of the Bashi-bulake Formation (Lan 1997). 

Ferganea ferganensis (Romanovskiy 1879) was endemic to Central Asia and, in all probability, was an euryhaline species well adapted to environmental fluctuations common in palaeogeographically restricted basins (Lan 1997).

The macrofossil analyses are in perfect agreement with our previous lithostratigraphic correlation with the last and fifth transgression in the SW Tarim Basin. Beyond that, the co-occurrence

Fig. 6. Continued.
Table 1. Macrofossil content and corresponding stratigraphic interpretation of examined samples

<table>
<thead>
<tr>
<th>Basin</th>
<th>Section</th>
<th>Code</th>
<th>Sample</th>
<th>Stratigraphic level (m)</th>
<th>Formation</th>
<th>Age (after Burtman 2000)</th>
<th>Fourth transgression</th>
<th>Fifth transgression</th>
<th>Non-age diagnostic</th>
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<tr>
<td>Alai Valley</td>
<td>Alai Valley</td>
<td>AL11</td>
<td>S02</td>
<td>± 5</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
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<td>Turkestan</td>
<td>Bartonian</td>
<td>–</td>
<td>x</td>
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<td>–</td>
<td>–</td>
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<td></td>
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<td></td>
<td>S02</td>
<td>± 430</td>
<td>Rishan-Sumsar</td>
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<td>TK11</td>
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<td>–</td>
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<td>S03</td>
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<td>S04</td>
<td>500.5</td>
<td>Suzak</td>
<td>Ypresian</td>
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<td>x</td>
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<td></td>
<td>S05</td>
<td>490.5</td>
<td>Suzak</td>
<td>Ypresian</td>
<td>–</td>
<td>x</td>
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<td>S05</td>
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<td>Rishan-Sumsar</td>
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<td>x</td>
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<td>Sumsar</td>
<td>Priabonian</td>
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<td>x</td>
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<td>Kuhdara</td>
<td>DS12</td>
<td>S01</td>
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<td>Givar</td>
<td>Ypresian</td>
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<td>Lutetian</td>
<td>–</td>
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</tr>
</tbody>
</table>
of *Platygena* and *Ferganea* in the stratigraphic interval at the base of the upper transgression suggests that the *Ferganea* species have a somewhat broader stratigraphic occurrence in the study region than previously reported, extending downwards to the base of the Isfara Formation.

**The Tash-Kumyr section.** Samples TK11-S05 and TK11-S04 comprise shells of *Flemingostrea ? hemiglobosa* (Romanovskiy 1884) (Fig. 6b: 10–16) confirming correlation with the Suzak Formation (Vialov 1948), which has been assigned an Ypresian age (Burtman 2000). This species has also been reported from the middle part of the Qimugen Formation in the Tarim Basin, which was deposited during the regression following the third marine incursion (Lan 1997), poorly constrained in age between the late Paleocene and early Eocene (Hao & Zeng 1984; Mao & Norris 1988; Tang *et al.* 1989; Zhong 1992; Lan & Wei 1995; Yang *et al.* 1995; Burtman 2000). According to Lan (1997), this extraordinary thick-walled sediment incliner represents the name-bearing species of the *Flemingostrea–Panopea* Assemblage Zone, marking a fully marine, subtidal setting with relatively warm seawater.

The presence of *Sokolowia buhsii* (Grewingk 1853) in sample TK11-S02 confirms the correlation with the Turkestan Formation (Vialov 1948). See the earlier subsection on ‘The Alai section’ for its palaeoenvironmental and palaeogeographical distribution.

*Glossus* (*Aralocardia*) *mica* (Ovechkin 1954) and *CrasSATella* (*Landinia*) *ustjurtensis* (Ilyina 1955) in sample TK11-S03 correlate to the upper Third Member of the latest Bartonian–early Priabonian Bashibulake Formation in SW Tajikistan (Lan 1997), and thus correlate with the *Ferganea*-bearing horizon of the previous section. Specimens from the Tarim Basin identified by Lan & Wei (1995) as *Glossus* (*Aralocardia*) *eichwaldiana* (Romanovskiy 1890) are identical to *Glossus* (*Aralocardia*) *mica* (Ovechkin 1954), and represent an erroneous identification based on its smaller size and distally increasing prominence of commarginal folds. *Glossus* (*Aralocardia*) *mica* (Ovechkin 1954), originally described from the upper part of the Priabonian Chegan Formation in western Kazakhstan (Ovechkin 1954; Krasheninnikov & Akhmetiev 1998), has been previously considered as restricted to the Hanabad Formation in the Afghan–Tajik Basin (Salibaev 1972). This study documents their nearness at the base of the Isfara Formation. *CrasSATella* (*Landinia*) *ustjurtensis* (Ilyina 1955) was originally recorded from the Priabonian of the Ustyurt Plateau in Central Asia (Lan & Wei 1995). This distribution of the infaunal glossids and crassatellids points to well-established palaeogeographical connections to the west, as well as to the east, during deposition of the Isfara Formation. These species are characteristic of low-energy, subtidal depositional settings. From TK11-S01, only two *Cordiopsis* sp. steinkerns are available, which have no biostratigraphic value.

**The Ala-Buka section.** Based on our lithostratigraphic correlation, the collected samples originate from the Rishtan, Isfara and Hanabad formations (Fig. 6a: 11; Fig. 6b: 1–8). Sample AB11-S01 was collected from shell beds at the same stratigraphic interval at the base of the upper transgression as sample UT-B02 of the Datka and Uch-Tobo sections (see the subsection on ‘The Datka and Uch-Tobo sections’) and has the same remarkable co-occurrence of *Platygena asiatica* (Romanovskiy 1879) and *Ferganea ferganensis* (Romanovskiy 1879). *Platygena* is an index species of the Rishtan Formation and *Ferganea* of the Isfara, Hanabad and Sumsar formations (Salibaev 1972), and both correspond to the marine members of the Bashibulake Formation representing the fifth marine incursion in the Tarim Basin (Lan 1997). As the transgressive sequence in the Ala-Buka section is condensed and constitutes only few tens of metres, their co-occurrence in the sampled stratigraphic interval fits with their previously established stratigraphic occurrence.

*Cubitostrea plicata* (Solander 1766) in AB11-S02 confirms the correlation with the Sumsar Formation (Salibaev 1972). This species occurs only in the Fourth Member of the Bashibulake Formation in the Tarim Basin (Lan & Wei 1995), and is a small-sized, shallow-water dweller, well adapted to turbulent water and environmental perturbation (Lan 1997). This species has a wide distribution and is known, for example, from Priabonian deposits of Bulgaria (Karagiuleva 1964).

**Bivalves from the Afghan–Tajik Basin**

*Platygena asiatica* (Romanovskiy 1879) can be excluded based on the highly globose
left-valve and the absence of a narrow dorsally elongated interior shell surface or glossy lamellae with *Camptonectes*-type macrosculpture on the shell exterior. See the earlier subsection on ‘the Tash-Kumyr section’ for the palaeoenvironmental and palaeogeographical distribution of *Flemingostrea? hemiglobosa* (Romanovskiy 1884). Sample DS11-S03 merely contains steinkerns of articulated infaunal bivalves *Cordiopis* sp. and *Glycymeris* sp., which have limited biostratigraphic significance and point to a subtidal marine depositional setting (Báldi 1973). The occurrence of *Ostrea* (*Turkostrea*) *strictiplicata* (Raulin & Delbos 1855) in sample DS12-S02 confirms the biostratigraphic position within the Jukar Formation (Dzialilov et al. 1982). The specimens are identical by right-valve and by left-valve to specimens illustrated in Stenzel (1971). Their possible classification with the Pliocene *Cubitostrea plicata* (Solander 1766) is excluded, as this species is larger in size and has a distinctly larger number of ribs on the left-valve. The Last Occurrence Datum (LOD) of *Turkostrea* is in the Alai Formation (Stenzel 1971), and it is very abundant in the lower and middle parts of the Lutetian Kalatar Formation, recording the transgression of the fourth incursion in the Tarim Basin (Lan 1997; Bosboom et al. 2014b). The ostreids are common in number and build bioherms (or reefs) in a lower subtidal–shallow subtidal setting (Lan 1997). *Ostrea* (*Turkostrea*) *strictiplicata* (= *Ostrea turkestanensis* Romanovskiy 1880) has also been reported from the Persian Gulf, being common in the middle Eocene of the Bahrain Island (Cox 1936).

**The Aksu section.** Correlation of the base of the section to the Jukar Formation is well supported by the oyster species from sample AS12-S01, identified as *Ostrea* (*Turkostrea*) *afganaica* (Vialov 1938) and as *Ostrea* (*Turkostrea*) *strictiplicata* (Raulin & Delbos 1855) (Fig. 6a: 2, 5) based on data from the Afghan–Tajik Basin by Vialov (1948). These species occur in the Alai Formation in northern Afghanistan (Cox 1938; Berizzi Quarto di Palo 1970). In the Tarim Basin, the species are common from the latest Paleocene to the middle Eocene in the *Ostrea* (*Turkostrea*) *afganaica*–*Sokolowia orientalis* Assemblage Zone of the Upper Qimugen Formation and in the *Ostrea* (*Turkostrea*) *strictiplicata*–*Ostrea* (*Turkostrea*) *cizancourti* Assemblage Zone of the Kalatar Formation, recording the regression following the third incursion and the transgression of the fourth incursion (Lan 1997). These species formed bioherms in lower intertidal and shallow subtidal, fully marine waters (Lan 1997). Whereas *Ostrea* (*Turkostrea*) *afganaica* (Vialov 1938) is restricted to Central Asia (Berizzi Quarto di Palo 1970), *Ostrea* (*Turkostrea*) *strictiplicata* (Raulin & Delbos 1855) has a much wider distribution, from the Tarim Basin up to the Bahrain Island in the Persian Gulf (Cox 1936).

**Synthesis**

The identified bivalve specimens largely confirm our lithostratigraphic correlation, showing that the SW Tarim Basin, Fergana Basin, Alai Valley Basin and Afghan–Tajik Basin share a similar geological history of shallow-marine third-order transgressions and regressions. The regional bivalve analyses show that the two studied incursions are each characterized by their own assemblage and depositional environment, and support correlation of the two studied incursion to the recognized and well-dated fourth and fifth incursions in the Tarim Basin. In addition, the bivalve species collected at the base of the Tash-Kumyr section in the Fergana Basin and at the base of the Kuhdara section in the Afghan–Tajik Basin correlate to the regressive interval preceding the fourth marine incursion.

**Discussion**

Based on our new litho- and biostratigraphic constraints, this study establishes for the first time a clear and detailed regional stratigraphic correlation between the basins across Central Asia from SW Tajikistan to NW China (Figs 2 & 7). The fourth and fifth marine incursions are each characterized by distinct lithofacies and assemblages of bivalves, which are very similar to the lithofacies and identified assemblages of the corresponding marine incursions recorded in the Eocene sedimentary successions of the Tarim Basin (Fig. 7). In the Afghan–Tajik Basin, no bivalve taxa representing the fifth marine incursion have been recovered; however, the corresponding strata correlate lithostratigraphically to bivalve-bearing deposits of the fifth incursion in the Alai Valley Basin, the Fergana Basin and the Tarim Basin. Hence, our correlation confirms that, during both the fourth and fifth marine incursions, the studied basins became unified as the shallow-marine epicontinental sea transgressed across Central Asia. The sedimentary successions of SW Tajikistan and southern Kyrgyzstan can now thus be convincingly linked to the previously established chronological framework of the last two marine incursions in the SW Tarim Basin, which have previously been dated as Lutetian and latest Bartonian–early Pliocene, respectively (Bosboom et al. 2014b, c). This allows us to evaluate the palaeoenvironment, palaeogeography, controlling mechanisms and palaeoenvironmental impacts of the long-term retreat of the proto-Paratethys Sea from Central Asia (Figs 1 & 8).
Palaeoenvironment and palaeogeography

As in the Tarim Basin, the marine depositional environment is generally characterized by fully marine, shallow-water, near-shore conditions. Warm-water carbonate platforms with shoals and bioherms of reef-building oysters are typical of the fourth transgression. Our preliminary lithostratigraphic correlation of this transgression shows that this incursion is more complex in the Afghan–Tajik Basin, where it comprises two stacked transgression–regression sequences separated by a prominent unconformity. The deposits of the fifth and last transgression primarily include subtidal–intertidal low-energy mudstones. In general, the bivalve species recorded in both transgressions have a wide palaeogeographical distribution as far as the Atlantic and the Indian oceans. However, the

Fig. 8. Preliminary palaeogeographical maps displaying the stepwise retreat of the proto-Paratethys Sea from Central Asia in the middle–late Eocene (a) and the isolation of the Paratethys Sea in the early Oligocene (b). Note that the coastlines are very approximate and based on Dercourt et al. (1993), Popov et al. (2004, 2010), Bosboom et al. (2011, 2014b, c) and the findings of this study. The suggested changes in palaeogeography shown in the Turgai Strait and Siberian Sea are based on Akhmetiev & Beniamovski (2006), Akhmetiev (2007) and Iakovleva & Heilmann-Clausen (2010), and from an extrapolation of the results of this study. Plate boundaries were obtained from GPlates 1.2.0 for 38 and 32 Ma. The stepwise retreat is time equivalent with significant aridification steps reported from the Xining Basin (Abels et al. 2011; Bosboom et al. 2014a).
present-day extent of the marine sediments of the fifth transgression is more limited, as shown by their absence at the palaeodeposcentre of the SW Tarim Basin and at the Kuhdara section in the Afghan–Tajik Basin. At the top of this final marine succession, the bivalve species *Ferganea*, which is an endemic genus of the easternmost basins of the proto-Paratethys originating within the fifth transgression, reflects the last marine pulse in the basins in Central Asia before their complete isolation (Figs 1 & 7).

As the sea entered and withdrew relatively rapidly across the SW Tarim Basin during the fourth marine incursion (Bosboom *et al.* 2014c) and as water depths are relatively shallow in these epicontinental basins (Bosboom *et al.* 2011, 2014c; this study), we concluded that the diachronity associated with transgressions and regressions across Central Asia was limited. Accordingly, we assume that the last marine deposits in Central Asia, which have been correlated to the latest Bartonian–early Priabonian fifth transgression of the Tarim Basin, are probably of late Eocene age. This correlation with the chronostratigraphic framework of the Tarim Basin implies that the base of the regressive Hissarak (in the Afghan–Tajik Basin) and Shurysay formations (in the Alai Valley and Fergana basins) overlying the last fully marine deposits are probably of late Eocene age, which is much older than the Oligocene age previously assigned (Fig. 2) (Markowsky 1959; Pomazkov 1972; Burtman 2000; Nikolaev 2002). Our correlation indicates that this late Eocene regression marks the end of the last major regional marine incursion and does not support a subsequent early Oligocene transgression, as suggested by Burtman (2000).

This new regional stratigraphic correlation allows us to update the palaeogeographical maps of the proto-Paratethys Sea (e.g. Dercourt *et al.* 1993; Rögl 1999; Popov *et al.* 2004, 2010) with the previously relatively unknown Central Asian palaeogeography of the two late Eocene marine incursions, as shown in Figure 8. Unless younger marine deposits have been eroded, our correlation of the last marine sediments suggests that the permanent disappearance of the sea from the studied basins would have occurred in the late Eocene. This final retreat of the proto-Paratethys Sea from Central Asia during late Eocene times fits with the palaeogeographical maps of Popov *et al.* (2004, 2010), which show that the Turan Sea largely covered Central Asia in the late Eocene, while, in the early Oligocene, the easternmost margin extended no further east than the area between the present-day East Aral and Syr-Darya basins. This is in agreement with the absence of organic-rich and mud-prone deposits in our studied sections, as these type of sediments have been reported from latest Eocene or early Oligocene records in the Black Sea and South Caspian basins, and have been interpreted as indicating the initial isolation and birth of the Paratethys Sea ( Báldi 1984; Rusu 1985; Dercourt *et al.* 1993; Robinson *et al.* 1996; Rögl 1999; Popov *et al.* 2004, 2008; Schulz *et al.* 2005; Vincent *et al.* 2005; Allen & Armstrong 2008; Johnson *et al.* 2009). However, the observed disconformity near the EOT in the SW Tarim Basin (Bosboom *et al.* 2014b) indicates that the Central Asian basins probably remained hydrologically connected to the western Tethys until the latest Eocene and had not yet established their present-day internal drainage configurations by basin closure.

**Controlling mechanism**

We previously discussed the cause of the sea retreat from the Tarim Basin, showing that probably a combination of long-term regional tectonism and superimposed short-term global sea-level fluctuations may have been responsible for the sea retreat (Bosboom *et al.* 2014b, c). This study indicates that the transgressions and regressions extended across a significant part of Central Asia, confirming that the underlying forcing mechanisms must have been operating over a large geographical range. Such mechanisms might have comprised: (1) distal tectonism and exhumation of the proto-Kunlun in response to the ongoing Indo-Asia collision, leading to widespread increased sedimentation within the large extent of the marine basin, which – with very low relief and transport capacity – was particularly susceptible to infilling from sedimentation; (2) eustatic sea-level fall, affecting an extensive area due to the shallow nature of the proto-Paratethys Sea; or (3) a combination of both.

In the Afghan–Tajik Basin, Alai Valley Basin and Fergana Basin, there is more evidence of tectonic activity than in the Tarim Basin. The nearly constant coarse-grained clastic input in most sections could be an expression of local tectonic deformation. Our sedimentological analyses in the Afghan–Tajik Basin show that this basin may have been particularly affected by tectonic instability at the top of the fourth marine incursion, as indicated by the presence of mica sandstones, reworking and slumping. These depositional instabilities may provide an explanation for the unconformity recognized within the fourth incursion, which has not yet been identified in the other studied basins of Central Asia. Hence, the thrust fronts of the western Pamir were probably more active and less distal compared to the West Kunlun Shan in the SW Tarim Basin. The mica sandstones are probably of volcanogenic origin sourced by Cenozoic granitoids in the western Central Pamir terrane (Schwab *et al.* 2004). However, studies on the tectonic evolution
of the western side of the Pamir in the Eocene are scarce and, apart from reports of accelerated exhumation of the north Central Pamir in the middle Eocene (Amidon & Hynek 2010), there is no evidence in support of Eocene tectonic activity near the Afghan–Tajik Basin. However, the lack of diachronism, the disconnection of the West Siberian Sea and the Turgai Strait from the Arctic Sea synchronous with the fourth regression in the late Lutetian (Akmetiev & Beniaminovskii 2006; Akmetiev 2007; Iakovleva & Heilmann-Clausen 2010), the late Eocene European regressions (e.g. Proust & Hosu 1996; López-Blanco et al. 2000; Lartaud 2007; Costa et al. 2010; Dawber et al. 2011) concomitant with the fifth regression in the late Priabonian, and the observed disconformity at the EOT in the SW Tarim Basin palaeodepocentre (Bosboom et al. 2014b, c) indicate that, superimposed on the long-term tectonically controlled westward trend, short-term eustatic sea-level changes probably forced the individual regressions. Comparison with the global sea-level curve of Komintz et al. (2008) shows that the two regressions studied here could be concomitant with minor drops in global sea level. Hence, these assertions further strengthen our previous concept of long-term westward retreat by early activation of the Pamir and superimposed short-term eustatic sea-level fluctuations that forced each individual regression step of the proto-Paratethys Sea from Central Asia.

Palaeoenvironmental impact

Previously, we showed that the sea-retreat steps from the westernmost margin of the Tarim Basin (Bosboom et al. 2014b, c) are contemporary with middle Eocene East Asian monsoon intensification (Quan et al. 2011, 2012) and aridification steps recorded near approximately 41 Ma (base C19n-base C18r) and 37.1 Ma (top C17n.1n) in the Xining Basin along the NW margin of the Tibetan Plateau (Abels et al. 2011; Bosboom et al. 2014a). This study shows that the early Priabonian fifth regression in the Tarim Basin may have been the onset of the permanent retreat from Central Asia, pushing the eastern margin of the sea from the westernmost Tarim Basin to the East Aral Basin (Popov et al. 2010), a shift of nearly 1000 km to the west (Fig. 8). Based on previous climate modelling results (Ramstein et al. 1997; Zhang et al. 2007), it is, indeed, likely that, after this major sea retreat, moisture supply to the Asian interior was permanently and significantly reduced. Zhang et al. (2007) showed that the key criterion for changing the palaeoenvironmental patterns in China was the retreat to the Turan Plate, which, as we suggest here, occurred after the final fifth transgression. The coeval timing of this regression from Central Asia and the major approximately 37.1 Ma aridification step is, hence, perfectly in line with these climate models and would confirm that the proto-Paratethys Sea had been an important moisture source for the Asian continental interior up until the late Eocene.

Conclusions

New macrofossil data from the Afghan–Tajik and Fergana basins and the Alai Valley Basin show that these basins experienced similar gradual third-order shallow-marine transgressions and regressions to the Tarim Basin. Both the fourth transgression of Lutetian age and the fifth transgression of latest Bartonian–early Priabonian age recognized in the Tarim Basin can be traced across Central Asia. The fourth transgression comprises two stacked transgression–regression sequences, and is characterized by relatively warm waters and dominated by carbonate shoals and a platform environment. The marine deposits of the fifth transgression are less widespread and comprise primarily low-energy subtidal and intertidal mudstones. Depositional instabilities and continuous clastic input show that the basins west of the Tarim Basin may have been more tectonically active owing to the early exhumation of the Pamir. After the fifth marine incursion into Central Asia, the eastern margin of the sea probably shifted hundreds of kilometres westwards, leading to strongly reduced moisture transport to the Asian interior in the late Eocene.

Our results provide a first-order framework of the sea retreat from the major incursion in the middle Eocene to its final retreat out of Central Asia in the late Eocene, extending the previous stratigraphic framework that we built up for the Tarim Basin further westwards. Potential controlling mechanisms and environmental impacts of the short-term sea-level fluctuations and long-term retreat are identified, but further high-resolution age control and detailed sedimentological work are required to ascertain the palaeogeographical dynamics of the proto-Paratethys Sea in Central Asia. Future magneto-, bio- and sequence-stratigraphic analyses, in particular, will enable the precise stratigraphic position, age and nature of the palaeogeographical changes identified in the studied basins to be pinpointed. This work is of utmost importance in making detailed correlations across large distances and, ultimately, offer the required resolution in both space and time to precisely track the evolution of palaeodepocentre migrations in Central Asia with respect to regional tectonism, palaeoenvironmental change in Asia and global sea-level variation.
The Netherlands Organization for Scientific Research (NWO) and DARIUS funded this project with grants to Roderic Bosboom and Guillaume Dupont-Nivet. We would like to thank Laurie Bougeois, Gloria Heilbronn, Jane Qiu, Rajabov Nematjon and Ilhom Oimahmadov for their contributions in the field. Our thanks also go to Franz Topka (NHM Vienna) for careful preparatory work on the mollusc material.

**Note added in proof**

Carrapa et al. (2015) report a Paratethys retreat ca. 39 Ma based on detrital zircon ages. This corresponds well to the 4th retreat recorded in the Beshkent formation correlated here to the Tarim Basin Wulagen Formation (Bosboom et al. 2014c). However, the final Paratethys regression should be attributed to the subsequent 5th marine transgression-regression reported here in the Kushan and Shanglak Formations and correlated to the Tarim Bain Bashibulake Formation. This 5th marine incursion is also shown in the upper part of the WA section of fig. 2 in Carrapa et al. (2015), several hundred meters above the ca. 39 Ma detrital zircons. The final retreat is hence sensibly younger than 39 Ma, assigned here to the latest Bartonian–early Priabonian.

### Appendices

An overview of the applied stratigraphic nomenclature and the corresponding lithostratigraphic descriptions, thicknesses and age estimates from Pomazkov (1972) and Dzhalilov et al. (1982) are given in Tables A1 & A2, respectively.

### Table A1. Simplified lithostratigraphic description and transgression–regression cyclicity for the Palaeogene stratigraphy of the Alai Valley Basin and Fergana Basin

<table>
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<th>Lithology</th>
<th>Formation</th>
<th>Sea level</th>
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<td>Palaeogene</td>
<td>Massaget Fm</td>
<td>Oligocene–Miocene</td>
<td>Massive red sandstones and conglomerates</td>
<td>Kezilouyi Fm</td>
<td>Continental</td>
<td></td>
</tr>
<tr>
<td>Sharysuy Fm</td>
<td>20–160 Oligocene</td>
<td>Brownish red-mudstones intercalated by siltstones, evaporite beds and sandstones</td>
<td>Bashibulake</td>
<td>Final fifth regression</td>
<td></td>
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</tr>
<tr>
<td>Sumsar Fm</td>
<td>0–70 Late Eocene–Oligocene</td>
<td>Reddish-brown mudstones and grey sandstones rich in oysters and other bivalves, shark teeth</td>
<td>Bashibulake</td>
<td>Final fifth transgression</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hanabad Fm</td>
<td>5–70 Late Eocene–Oligocene</td>
<td>Greenish-grey and red (calcareous) mudstones and siltstones, some marls with bivalves</td>
<td>Bashibulake</td>
<td>Third Member</td>
<td></td>
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<tr>
<td>Issara Fm</td>
<td>5–55 Late Eocene</td>
<td>Greenish-grey (calcareous) mudstones and siltstones, some green or white sandstones, some marls with bivalves</td>
<td>Bashibulake</td>
<td>Second Member</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rishtan Fm</td>
<td>5–60 Late Eocene</td>
<td>Red mudstones with thin beds of red or grey siltstone and sandstone, some interbeds of marl and limestone with bivalves</td>
<td>Bashibulake</td>
<td>First Member</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Turkestan Fm</td>
<td>5–150 Middle–late Eocene</td>
<td>Greenish-grey mudstones with grey and white siltstones, sandstones, marls and limestones, red mudstone intervals at the top, rich in oysters and other bivalves</td>
<td>Wulagen Fm</td>
<td>Fourth transgression</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alai Fm</td>
<td>10–210 Middle Eocene</td>
<td>Greenish-grey mudstones with grey and white siltstones, sandstones, marls and limestones, red mudstone intervals in middle, rich in oysters and other bivalves</td>
<td>Kalatar Fm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Suzuk Fm</td>
<td>5–120 Early Eocene</td>
<td>Complex coloured (calcareous) mudstones, siltstones and sandstones, bivalves</td>
<td>Upper Qimugen Fm</td>
<td>Third regression</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bukhara Fm</td>
<td>20–80 Paleocene</td>
<td>Limestones, evaporite beds and white sandstones with thin calcareous mudstone layers, bivalves and gastropods</td>
<td>Lower Qimugen Fm</td>
<td>Third transgression</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Akdrzhar Fm</td>
<td>25–125 Paleocene</td>
<td>Red mudstones and siltstones with interbeds of evaporite and dolomite</td>
<td>Aertashi Fm</td>
<td>Second regression</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The corresponding thicknesses and ages of the formations are not to scale and are summarized from Pomazkov (1972). Correlation with the stratigraphic framework of the Tarim Basin is based on results of this study.
Table A2. Simplified lithostratigraphic description and transgression–regression cyclicity for the Palaeogene and early Neogene stratigraphy of the Afghan–Tajik Basin

<table>
<thead>
<tr>
<th>Afghan–Tajik Basin (Tajikistan)</th>
<th>Thickness (m)</th>
<th>Age</th>
<th>Lithology</th>
<th>Formations</th>
<th>Sea level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neogene Baldzhuan Complex Kamoli</td>
<td>180–310</td>
<td>Miocene</td>
<td>compact massive and coarse laminated red sandstones with rare interbeds of mudstones, siltstones and conglomerates</td>
<td>Kezilousyi Fm</td>
<td>Continental</td>
</tr>
<tr>
<td>Palaeogene Shurysay Fm</td>
<td>0–190</td>
<td>Oligocene</td>
<td>Reddish-brown mudstones, sandstones and siltstones with gypsum, rare interbeds of limestone</td>
<td>Bashibulake Fifth Member</td>
<td>Final fifth regression</td>
</tr>
<tr>
<td></td>
<td>0–130</td>
<td>Oligocene</td>
<td>Greenish-grey sandstones and reddish-brown mudstones, siltstones and sandstones, rare gypsum interbeds and stromatolites at the base</td>
<td>Bashibulake Fifth Member</td>
<td>Final fifth regression</td>
</tr>
<tr>
<td></td>
<td>0–90</td>
<td>Middle–late Eocene</td>
<td>Brownish-red mudstones with red-brownish-grey sandstones at the top, bivalves</td>
<td>Bashibulake Fourth Member</td>
<td>Final fifth transgression</td>
</tr>
<tr>
<td></td>
<td>0–175</td>
<td>Middle–late Eocene</td>
<td>Greenish-grey (calcareous) mudstones with rare interbeds of limestones and shell beds, at the top reddish-brown mudstones</td>
<td>Bashibulake Third Member</td>
<td>Bashibulake Second Member</td>
</tr>
<tr>
<td></td>
<td>Upper 0–175</td>
<td>Middle–late Eocene</td>
<td>Red mudstones, siltstones and sandstones, bivalves</td>
<td>Bashibulake First Member</td>
<td>Fourth regression</td>
</tr>
<tr>
<td></td>
<td>Lower 0–40</td>
<td>Middle–late Eocene</td>
<td>Grey sandstones with mudstone and white gypsum at the top</td>
<td>Wulagen Fm</td>
<td>Fourth transgression</td>
</tr>
<tr>
<td>Beshkent Gandzhin layers Turkestan layers</td>
<td>0–60</td>
<td>Middle Eocene</td>
<td>Greenish-grey calcareous mudstones with interbeds of marls, shell beds, limestones and sandstones</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0–130</td>
<td>Middle Eocene</td>
<td>Greenish-grey mudstones with rare shell beds</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>20–240</td>
<td>Middle Eocene</td>
<td>Greenish-grey mudstones, marls, limestones, shell beds and some sandstones, red mudstones, dolomites and gypsum interbeds</td>
<td>Kalatar Fm</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5–130</td>
<td>Early Eocene</td>
<td>Grey mudstones, oysters</td>
<td>Upper Qimugen Fm</td>
<td>Third regression</td>
</tr>
<tr>
<td></td>
<td>0–40</td>
<td>Paleocene</td>
<td>Grey calcareous mudstones, marls and muddy limestones</td>
<td>Lower Qimugen Fm</td>
<td>Third transgression</td>
</tr>
<tr>
<td></td>
<td>0–60</td>
<td>Paleocene</td>
<td>Grey calcareous mudstones, marls and limestones, gypsum beds and dolomite at the top, molluscs</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>5–130</td>
<td>Paleocene</td>
<td>Limestones with rare beds of dolomite and gypsum, bivalves</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>10–250</td>
<td>Paleocene</td>
<td>Gypsum, dolomites and red mudstones, some interbeds of red siltstones and sandstones, bivalves</td>
<td>Aertashi Fm</td>
<td>Second regression</td>
</tr>
</tbody>
</table>

The corresponding thicknesses and ages of the formations are not to scale and summarized from Dzhalilov et al. (1982). Correlation with the stratigraphic framework of the Tarim Basin is based on results of this study.
References


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Palaeogeography of the Proto-Paratethys Sea


