Tectono-climatic implications of Eocene Paratethys regression in the Tajik basin of central Asia

Barbara Cararapa, Peter G. DeCelles, Xin Wang, Mark T. Clementz, Nicoletta Mancin, Marius Stoica, Brian Kraatz, Jin Meng, Sherzod Abdulov, Fahu Chen

Department of Geosciences, University of Arizona, Tucson, AZ, USA
Key Laboratory of Western China’s Environmental Systems (Ministry of Education), Lanzhou University, Lanzhou, China
Department of Geology and Geophysics, University of Wyoming, Laramie, USA
Department of Earth and Environmental Sciences, University of Pavia, Italy
Department of Geology and Paleontology, Faculty of Geology and Geophysics, Bucharest University, Bilăcescu, Romania
Western University of Health Sciences, Pomona, USA
American Museum of Natural History, New York, USA
Institute of Geology, Earthquake Engineering and Seismology of the Academy of Sciences, Tajikistan

A R T I C L E   I N F O

Article history:
Received 9 March 2015
Received in revised form 14 May 2015
Accepted 18 May 2015
Available online xxxx
Editor: A. Yin

Keywords:
Paratethys
Tajik basin
Tarim basin
foreland basin
Pamir
Tibet

A B S T R A C T

Plate tectonics and eustatic sea-level changes have fundamental effects on paleoenvironmental conditions and bi-ecological changes. The Paratethys Sea was a large marine seaway that connected the Mediterranean Neotethys Ocean with Central Asia during early Cenozoic time. Withdrawal of the Paratethys from central Asia impacted the distribution and composition of terrestrial faunas in the region and has been largely associated with changes in global sea level and climate such as cooling associated with the Eocene/Oligocene transition (EOT). Whereas the regression has been dated in the Tarim basin (China), the pattern and timing of regression in the Tajik basin, 400 km to the west, remain unresolved, precluding a test of current paleogeographic models. Here we date the Paratethys regression in Tajikistan at ca. 39 million years ago (Ma), which is several million years older than the EOT (at ca. 34 Ma) marking the greenhouse to icehouse climate transition of the Cenozoic. Our data also show a restricted, evaporitic marine environment since the middle–late Eocene and establishment of desert like environments after ca. 39 Ma. The overall stratigraphic record from the Tajik basin and southern Tien Shan points to deposition in a foreland basin setting by ca. 40 Ma in response to active tectonic growth of the Pamir–Tibet Mountains at the same time. Combined with the northwestward younging trend of the regression in the region, the Tajik basin record is consistent with northward growth of the Pamir and suggests significant tectonic control on Paratethys regression and paleoenvironmental changes in Central Asia.

© 2015 Elsevier B.V. All rights reserved.

1. Introduction

During early Cenozoic time the Paratethys Seaway (Popov et al., 2004), a northern branch of the Neotethys Ocean, connected the central Atlantic Ocean with a complex system of basins, covering a roughly 1200 km wide and >3000 km long east–west swath of Europe and southern central Asia (Fig. 1). The eastern extremity of this vast region is now occupied by the Tibet–Pamir orogenic sys-tem and related sedimentary basins including the Tajik and Tarim basins.

Aridification and monsoonal climate in Asia have been linked to transgressive–regressive cycles of the Paratethys and global climatic changes (Bosboom et al., 2011, 2013, 2014a, 2014b; Dupont-Nivet et al., 2007; Licht et al., 2014). In particular, the study by Bosboom et al. (2014a) suggests a stepwise westward retreat of the Paratethys between 41 Ma and 37 Ma. Although this study is important for paleogeographic reconstruction of the Paratethys, no data exist from the Tajik basin, located ~400 km to the west of the Tarim basin (Fig. 1). Therefore, the relative controls of tectonics and global climate on the retreat of the Paratethys remain unresolved. Competing models attribute aridity and mon-
sonal climate in central Asia to the Tibetan Plateau (e.g., Molnar et al., 2010). The timing of Paratethys regression and attainment of high topography and elevations in the region are thus critical for evaluating current climate and tectonic models.

A several km thick succession of Cenozoic sedimentary rocks deposited in the Tajik basin (Nikolaev, 2002) preserves a record of paleoenvironmental changes, erosion and tectonic activity of the surrounding Pamir and Tien Shan Mountains. This study applies sedimentology, paleontology, sandstone petrography and zircon U–Pb geochronology to lower Cenozoic deposits in the Tajik depression and southern Tien Shan to constrain the timing of Paratethys regression in Tajikistan and to understand changes in depositional environments in response to tectonics and climate. The zircon geochronology (from a volcanic tuff) anchors the transition from marine to non-marine deposition at ca. 39 Ma in the region. This datum is the first radiometric age ever reported from Paratethyan rocks in central Asia, and also constrains the time of the regression in Tajikistan to \( \sim \) 39 Ma. The 39 Ma age is significantly older than global sea-level changes and biotic turnovers of the Eocene/Oligocene transition (EOT) at ca. 34 Ma. When compared with the relative timing of the regression available for the Tarim basin, ranging from ca. 41 Ma to ca. 37 Ma (Bosboom et al., 2014a), our study suggests a northwestward younging of the regression consistent with northward growth of the Pamir Mountains and development of a foreland basin system in the area now occupied by the Tajik–Tarim basins by late Eocene time. Growth of the Pamir in the Cenozoic has most likely affected land–sea distributions and climate in Central Asia.

2. Geological setting

The Tajik basin was connected with the Tarim basin during the early Cenozoic, but subsequent northward growth of the Pamir orogen has severed this connection. The geologic history of the Tajik and western Tarim basins (Fig. 1) is thus crucial to understanding the tectonic evolution of the Pamir and the Tajik–Tarim connection through the Paratethys Seaway. The Paratethys Seaway was part of a larger epicontinental sea that connected the Mediterranean Tethys to the Tarim basin until at least the early Cenozoic.
It covered a vast area and as such probably had a major effect on paleoenvironments and climate in central Asia. 

During the EOT, the Paratethys Seaway was surrounded by land and connected to the Mediterranean Tethys and other oceans through narrow passages. The Paratethys Seaway was located upwind from and served as a major moisture source for the Tarim basin and large parts of continental Asia.

The westward retreat of the Paratethys Seaway has been primarily associated with eustatic sea level changes (Bosboom et al., 2013, 2014a, 2014b). Eocene–Oligocene redbeds and late Miocene loessite in China are interpreted as indicating arid climate and winter monsoonal conditions (Bosboom et al., 2014a; Licht et al., 2014) related to either orographic effects associated with the Tibetan Plateau (Molnar et al., 2010) or a combination of tectonics and global sea level changes affecting Paratethys regression and global cooling (e.g., Bosboom et al., 2014b; Dupont-Nivet et al., 2007). Although growth of the Pamir has been loosely suggested as a possible control on paleoenvironmental changes in Central Asia, the role of the Pamir on Paratethys regression and timing of tectonic activity remain largely unconstrained. An orographic effect associated with the Pamir has been suggested to have played a significant role on erosion since the Miocene (Carrapa et al., 2014); however, uplift and northward growth of the Pamir and its possible effect on paleoenvironments during the early Cenozoic is not known.

Data from the Tibetan Plateau suggest significant shortening and crustal thickening during the Cretaceous and early Cenozoic (Yin and Harrison, 2000; Kapp et al., 2005) consistent with high elevations of at least parts of Tibet since the Eocene. Palealitimetry data indicate high elevations since at least the late Oligocene in central Tibet (DeCelles et al., 2007). The Pamir, which is the western continuation of the Tibetan Plateau (Yin and Harrison, 2000; Robinson et al., 2012), preserves evidence of thick crust and Oligo-Miocene high-grade metamorphism and exhumation (e.g., Schmidt et al., 2011) but its earlier tectonic history remains largely unknown, leaving open the question of its potential role in controlling land–sea reorganizations and Asian climate during the early Cenozoic.

In the Tarim basin, Paratethys regression has been dated between ca. 47 and 37 Ma (Bosboom et al., 2011, 2013, 2014a; Sun and Jiang, 2013). In particular, Bosboom et al. (2014a) suggested a million-year-scale stepwise retreat of the Paratethys in the Eocene, consistent with a tectonic control, and hydrological connection between the Tarim and Tajik basins until ca. 34 Ma.

3. Methods

3.1. Field work and stratigraphic correlations

We investigated three widely spaced Paleogene stratigraphic sections, up to 1500 m thick, within the Tajik basin (Figs. 1 and 2; WA and PE) and southern Tien Shan (ZD) and measured them at the m scale using a Jacob's staff. Out of a total of 130 samples collected, 48 were selected, on the basis of paleontological content and mineral yield, for biostratigraphic, geochronologic, petrogenetic, and sedimentologic analyses. Facies analysis and interpretations of paleodepositional environments are based on detailed stratigraphic sections presented in Fig. 2. Facies were identified and recorded using the classification scheme of Miall (1978) (Supplementary material; Table S1). Correlations between sections were based on facies, fossil assemblages, and zircon U–Pb geochronological data.

3.2. Biostratigraphy

Microfossil analyses were performed on sixteen samples from all three sections; however, only samples from the ZD section contained suitable microfossils (ostracods, planktonic foraminifera and calcareous nannofossils) for age determination (Fig. 2); samples from the WA sections were barren and only a few samples from the PE section contained limited foraminifera (Supplementary material; Table S2).

Samples were disaggregated by mortar and washed and sieved through meshes of 180 and 125 μm; the washed residues were then dried in an oven at about 40°C. Approximately 200 foraminifera were counted under a stereomicroscope in random aliquots of both the >180 and 180–125 μm washed fractions to obtain census counts of the more common species recorded in the studied samples. Census counts are reported in the Supplementary material (Table S2). Planktonic foraminiferal taxonomy follows the guide of Toumarkine and Luterbacher (1985) partly updated by Pearson et al. (2012). The biostratigraphic attribution is primarily based on the standard zonations (Berggren and Pearson, 2005; Wade et al., 2011). The same washed residues analyzed for foraminifera were investigated also for ostracods.

For nannofossil analyses, simple smear-slides were prepared from the same ZD samples used for foraminiferal study and were analyzed under a polarizing light microscope at 1250X magnification. The nannofossil abundance was quantified by counting all the nannofossil specimens occurring in 400 random fields of view, corresponding approximately to an area of 6 mm², in each sample. The biostratigraphic attribution is primarily based on standard zonations (Martini, 1971; Okada and Bukry, 1980). Results are reported in the Supplementary material (Table S2).

Invertebrate fossils, primarily shells of bivalves of the orders Ostreida and Pectinida, were observed in the PE, WA, and ZD sections. When of suitable quality, specimens were identified to lowest taxonomic-level following previous studies (Lan, 1997) and were compared with faunas of comparable age from the Tarim basin (Bosboom et al., 2011, 2013, 2014a).

3.3. U–Pb geochronology of detrital zircons (Nu HR ICPMS)

Zircon crystals were extracted from six selected samples by traditional methods of crushing and grinding, followed by separation with a Wilfley table, heavy liquids, and a Frantz magnetic separator. Samples were processed such that all zircons were retained in the final heavy mineral fraction. A large split of these grains (generally several hundreds of grains) was incorporated into a 1” epoxy mount together with fragments of our Sri Lanka standard zircon. The mounts were sanded down to a depth of ~20 μm, polished, imaged, and cleaned prior to isotopic analysis. U–Pb geochronology of zircons was conducted by laser ablation multi-collector inductively coupled plasma mass spectrometry (LA-MC-ICPMS) at the Arizona LaserChron Center (Gehrels et al., 2008). 100 grains were targeted for sandstone samples and 38 grains for the volcanic tuff; results are shown in Fig. 3. Additional analytical information can be found in the Supplementary material (Table S3).

3.4. Sandstone petrography

Modal sandstone petrographic data were collected from six selected standard petrographic thin sections from medium-grained sandstones from the WA and PE measured sections (Fig. 2). Each thin section was stained for calcium and potassium feldspars and 450 grains were counted according to the Gazzì-Dickinson method (Ingersoll et al., 1984). Results are shown in Fig. 4 and additional material and information can be found in the Supplementary material (Tables S4, S5).

3.5. SEM and grain size analyses

Three hundred and eighty bulk samples were collected from the lower part of the PE section (0–850 m) for grain size analysis.
Fig. 2. Measured stratigraphic sections from the Tajik basin (PE and WA sections) and southern Tien Shan (ZD section); facies codes and facies associations are described in Table S1 in the Supplementary material.
Twenty samples from eolian dune and loessite strata within the PE section were selected for Scanning Electron Microscope (SEM) analysis. Each sample was treated with 10% H₂O₂ and 10% HCl to remove organic matter and carbonates, and the grain morphology was observed on a Hitachi S4800 SEM. 2–4 g of air-dried material for each sample was firstly treated with 10 ml of 10% H₂O₂ to remove organic matter and with 10 ml of 10% HCl to remove carbonates; 100 ml of distilled water was then added and the sample solution was kept for 12 h to rinse acidic ions. The sample residues were dispersed with 10 ml of 0.5 N (NaPO₃)₆ in an ultrasonic vibrator and were measured on a Malvern Mastersizer 2000 laser grain-size analyzer. All the pretreatments and measurements were performed in the Key Laboratory of Western China’s Environmental systems, Lanzhou University. Results are presented in Fig. 5.

4. Results and interpretations

4.1. Sedimentology and depositional environments

The studied sections are dominated by fine-grained siliciclastic and carbonate lithofacies in their lower parts and sandstone in their upper parts. Lithofacies exhibit an overall transition up-section from shallow marine to continental characteristics (Fig. 2). The shallow marine to marginal marine deposits are characterized by black to predominantly green–gray colors (Supplementary material, Fig. S1) and oolitic grainstone, fossiliferous packstone, laminated carbonate mudstone, dolomitic marl, calcarenite, and rippled fine-grained sandstone with occasional gypsum. Gypsum was identified in deposits of the ZD section and tufa mounds were identified in section WA (Fig. 2) indicating shallow–marginal marine
facies and warm, restricted water (Winsor et al., 2012). A single bed (20 cm thick) of white volcanic ash crops out at the 47 m level of section PE, within the transition between marine and non-marine deposits (Fig. 2).

Fluvial facies generally consist of red, trough cross-stratified and rippled sandstone, and laminated to massive siltstone typical of high-sinuosity fluvial deposits (Fig. 2; Supplementary material). In section ZD massive red siltstone with mottles and carbonate nodules is interpreted as calcic paleosols. Red siltstones with occasional oscillatory current ripples are interpreted to represent a transitional environment (possibly tidal flats) (Dalrymple and Choi, 2007).

Eolian deposits are characterized by large-scale (several meters thick) cross-stratified sandstone (foresets) with planar tops and tangential bases, trough cross-stratified and rippled sandstone, and siltstone typical of eolian dune and interdune deposits (Kocurek, 1981) (Figs. 2, 5). Massive (structureless), homogeneously sorted, but disorganized (massive) and poorly consolidated red sandstone and siltstone are interpreted as eolian loess deposits (Figs. 2, 5) similar to sandy loess described by Zheng et al. (2003) from the southern Tarim basin. Scanning electron microscopy (SEM) of sand grain surface textures and grain-size analyses confirm this interpretation (see below).

4.2. Invertebrate paleontology

Typical macrofossils of marine strata from the investigated sections include epifaunal bivalves of the orders Pectinida and Ostreida, supporting a shallow-marine environment. Trace fossils include Skolithos, which is typical of marginal and shallow marine environments.

Ostreida fossils (e.g., oysters) indicate eutrophic conditions (i.e., high nutrient, high content of organic matter); the best specimens of these bivalves were collected from levels in the ZD section and were identified (Dr. Oleg Mandic, pers. comm.) as belonging to the species Sokolowia buhsii (Supplementary material; Fig. S2). The same species has been described in deposits from the Tarim basin and interpreted to be middle–late Eocene in age (late Lutetian to early Priabonian) (Bosboom et al., 2011).

4.3. Foraminifera and calcareous nanofossils

Planktonic foraminifera from the PE and WA sections are rare or missing and scarcely preserved (Supplementary material; Table S2); only in one sample from the PE section (PE42), very rare marker species (Acarinina gr. brodermanni, TurboRotalia corozuensis corozuensis and Pseudohastigerina micra) are obtained, which are indicative of a middle–late Eocene age (Bartonian–early Priabonian). Planktonic foraminiferal assemblages are quite well preserved but less abundant and diverse in ZD section from the southern Tien Shan. In samples ZD-062 (1–2) planktonic foraminifera do not exceed 5% of the total foraminiferal assemblages and their abundance decreases up-section (<1% in samples ZD-063 (1–2)). The marker species are always very rare and quite discontinuously distributed; nevertheless the co-occurrence of the species Morozovella formosa, M. aragonensis and M. subbotiniae suggest an Ypresian age (E4–5 Zones; Berggren and Pearson, 2005) for sample ZD-062 (1–2). The poor planktonic assemblages and the possibility of reworking do not, however, exclude a younger age.

Benthic foraminifera from the PE section are less abundant and mostly characterized by textulariids, Cibicides and other rotaliids such as the genera Ammonia and Rotalia; these two genera usually inhabit shallow water environments and are typical of the littoral zone (e.g., Van Morkhoven et al., 1986). On the contrary, benthic foraminifera from the lower ZD section (samples ZD-062 and 063, Fig. 2) are usually very abundant, quite well preserved,
and mostly characterized by agglutinated taxa. The overall benthic foraminiferal fauna (Table S2) is composed of representatives of the agglutinated genera *Tritaxia, Textularia, Psammosphaera, Spiroplectammina, Dorothis* and *Reophax* together with the calcareous hyaline genera *Cibicidoides* (both biconvex and planoconvex morphotypes), *Anomalinoidea*, *Praeglobobulimina* and *Lenticulina* with rare to very rare admixtures of representatives of *Pullenia, Trifaria, Vaginulinops*, *Oridorsalis* (mostly *O. umbonatus*) and fragmented nodosariids (*Nodosaria, Vaginulina, Dentalina*). We note that the benthic foraminiferal assemblage is characterized by mixed shallow and deep water index taxa (e.g., Jorissen et al., 2007 and references therein). Specimens of *Lenticulina* spp., *Nodosaria* and of the species *Oridorsalis umbonatus* and *Anomalina pomplioides*, all indicative of upper depth limit distribution of ca. 600–1000 m, co-occur with shallower-water indexes (such as *Tri-taxia, Textularia, Spiroplectammina, Dorothis* and *Reophax*) that are typical of the neritic domain (<200 m water depth). The mixed foraminiferal assemblage is interpreted to be the result of reworking. The studied washed residues also contain rare fish teeth, sea-urchin spines and gypsum crystals, which are particularly abundant in samples ZD-063 (1–2) and are consistent with an evaporitic environment.

In general, nannofossil abundance and preservation are quite limited in the ZD samples (1–2) (Table S2); the other collected samples are barren of nannofossils. In the studied assemblages, the co-presence of *Discoaster dyastipus* and *D. multiradiatus*, and the absence of *Discoaster lodoensis* and *Tribrachiatus contortus*, suggest an Ypresian age (NP11 Zone) (Martini, 1971); however, this assemblage may be reworked, similar to our interpretation for the foraminifera assemblage.
4.4. Ostracods

Ostracods were only available for the ZD section and are very rare and poorly preserved. The specimen from the sample ZD-062 (1) (Supplementary material; Fig. S3) is recognized as Cytheridea eocaenica, which has been described in Priabonian deposits from the Bashibulake Mine section in the Tarim basin (Bosboom et al., 2014a). C. eocaenica is also described in the Oligocene of southern Romania (Olteanu, 2006). Sample ZD-062 (1) also contains the genus Loxononcha (Fig. S3, images C, D, E). We note that the species Loxononcha ex. gr. nystiana occurs from late Eocene to Oligocene (Keen, 1978; Printkens and Berger, 2011) and has been found in deposits from the Tarim Basin that were interpreted to be late Eocene in age (Bosboom et al., 2011). Fragments from sample ZD-063 (1) (Fig. S3, images A, B) and complete shells from sample ZD-063 (2) are identified as the species Cytheridea ex. gr. pernota, which is one of the most common species described in the Tarim basin in the upper Eocene (Bosboom et al., 2011); although, the same species is also mentioned from the lower Oligocene of western Europe.

The specimen from sample ZD-063 (2) (Fig. S3, images A, B) is difficult to identify but it may represent the anterior part of the genus Pterigocythereis. The species P. ceratoptera has been identified in Priabonian strata from the Tarim basin (Bosboom et al., 2014a). The same species has been described from the upper Rupelian of the upper Rhine Graben, the Oligocene of the Paris Basin and the lower Rupelian from the Swiss Jura (Ducasse et al., 1985; Picot et al., 2008; Printkens and Berger, 2011). This marine genus is used as a fossil marker for water depth, indicating minimum water depth of approximately 60 m in open marine coasts and less than 10 m in restricted marine environments (e.g., Libeau, 1980). Overall the ostracod assemblages suggest a late Eocene–early Oligocene age for the lower part of the ZD section.

4.5. Integrated biostratigraphy and chronostratigraphy

The paleontological data described above are apparently in disagreement: oyster and ostracod assemblages indicate a mostly late Eocene to early Oligocene age, whereas the foraminiferal and nannofossil assemblages, coming from the same ZD samples, indicate an older early Eocene (Ypresian) age. These results can be explained by erosion and reworking of older foraminiferal and nannofossil taxa derived from Ypresian strata and later deposition as residues in late Eocene–early Oligocene deposits. The scarcity of younger (late Eocene–lower Oligocene) foraminiferal and nannofossil specimens in our samples could be justified by the particular depositional conditions. It is plausible that in a shallow and restricted marine environment, characterized by deposition of gypsum (indicative of an evaporitic environment with a restricted circulation and high salinity), the paleontological assemblages were scarce and mostly made of heavy-shelled mollusks and ostracods, while foraminifera (mostly the planktonic specimens) and nannofossils were very rare to absent. Also, in the ZD section we find exclusively planktonic foraminifera and nannofossil specimens older in age and benthic foraminifera indicative of both neritic and deepwater conditions (depth below 600 m), which are inconsistent with the sedimentological and other paleontological data reinforcing the interpretation that these assemblages are reworked residues. Instead, the biostratigraphic data from the lower portion of the PE section (sample PE-042) indicates a late Bartonian–early Priabonian age. This is consistent with the age derived from ostracod and oyster assemblages for the lower portion of the ZD section.

4.6. Geochronology and sediment provenance

The volcanic ash layer at the 47 m level of section PE produced a zircon U–Pb final age of 38.93±0.54 Ma (Fig. 3). Because this ash layer is located within the transition from marine to non-marine facies, it provides the only absolute geochronological age constraining the timing of the transition from marine to continental environments during the middle Eocene (Bartonian) in Tajikistan.

Zircon U–Pb ages from five detrital sandstone samples from the ZD, WA, and PE sections (Figs. 2 and 3) show a strong 40 Ma signal, typical of Pamir rocks (Lukens et al., 2012; Bershaw et al., 2012). This requires that the depositional ages of the host sedimentary strata must be younger than ~40 Ma and suggests active magmatism (U/Th ratios <1; Supplementary material, Table S3) in the sediment source area at this time.

Modal petrographic compositions of selected sandstones from the investigated strata document provenance typical of foreland basin deposits (e.g., Dickinson, 1974) (Fig. 4). Sandstone framework grain modes are dominated by quartzo lithic compositions, plagioclase feldspar, and heterogeneous labile lithic populations. On quartz–feldspar–lithic grain diagrams, the samples plot in the recycled orogenic and magmatic arc provenance fields, typical of sandstones deposited in retroarc foreland basins. The most important lithic grain types include quartz–mica tectonite, quartz–mica schist, micritic limestone, and various types of intermediate volcanic lithic grains (Supplementary material; Tables S4 and S5). Volcanic lithic grains indicate active magmatism in the source regions during the time of deposition, consistent with the abundance of ca. 40 Ma detrital zircon U–Pb ages and the presence of the ~39 Ma volcanic ash layer in section PE.

4.7. Characterization of eolian deposits

SEM analyses were performed on eolian sandstone and loesite from the PE section deposited on top of the last marine interval (Fig. 2). A majority of the grains, mostly quartz, from eolian dune and loess strata, have irregular shapes often characterized by sharp edges and conchoidal surfaces (Fig. 5) that are characteristic of eolian deposits (Whalley et al., 1982). Grain-size distributions of eolian dune sandstone from the PE section are bimodal (Fig. 5I) with a well-sorted coarse component (ca. 150 μm) and a poorly-sorted fine component (ca. 10 μm). Grain-size distributions of eolian loess material have trimodal distributions (Fig. 5I), with a well-sorted coarse component (ca. 50 μm), a poorly sorted fine component (ca. 10 μm), and a minor ultrafine component (<2 μm). Our data are consistent with the grain-size distribution of modern eolian dune and loess deposits from western China (Sun et al., 2002). The grain morphology, grain-size distribution and lithological evidence further confirm the eolian origin of these strata (Whalley et al., 1982).

5. Discussion

The sedimentology, paleontology and geochronology of the investigated sections suggest that a marginal marine environment and restricted conditions were present during mid–late Eocene time and a transitional to fluvial environment was established by ca. 39 Ma in the Tajik depression. Similar facies in the Tajik basin and southern Tien Shan indicate that the two regions were part of the same basin filled by detritus derived from the nascent Pamir. Furthermore, our data imply that the Tien Shan did not exist as a topographic feature during the late Eocene–early Oligocene and instead a continuous basin covered the region between the Pamir and southern Tien Shan.

A restricted evaporitic marine environment was established in the late Eocene–early Oligocene as indicated by the presence of gypsum and tufa mounds typical of arid coastal conditions. More than 1000 m of eolian deposits (sand dunes and loess) on top of the last marine interval (PE section) indicate that a desert-like environment was established directly following Paratethys regression. Our results are consistent with data from the Chinese Loess Plateau.
Fig. 6. (A) Digital elevation model of the study area with location of the sections investigated in this study and in Bosboom et al. (2011, 2013, 2014a, 2014b, 2014c) used for comparison; (B) modified sea level curve based on the New Jersey record (Cramer et al., 2011) and PETM global regression–transgression sequences. (C) Paleogeographic cartoon showing timing of Paratethys regression (blue: marine; gray: continental/uplifting area) based on this study and literature data; sample locations as in A. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

and the Tarim basin, indicating that aridity was established by the Oligocene (Bosboom et al., 2013) and as early as 40 Ma (Bosboom et al., 2014a, 2014c).

Aridification in central Asia has been linked to a global cooling trend following the early Eocene, characterized by climatic variability (e.g. Middle Eocene climate optimum) and leading to the Eocene–Oligocene transition (Dupont-Nivet et al., 2007; Bosboom et al., 2014c). The EOT corresponds with an abrupt decline of atmospheric CO2 concentration and associated glaciation in Antarctica (Pagani et al., 2011; Zachos et al., 2008) around 34 Ma. Paratethys regression in the Tarim basin of Central Asia has been linked to global sea level fall related to Eocene–Oligocene cooling (Bosboom et al., 2014a). However, the correlation between the Tajik basin stratigraphic record of Paratethys regression and global sea level shows that marine regression predated the EOT by as much as 4.8 million years in Tajikistan (Fig. 6). Combined with data from the Tarim basin, our study indicates that the marine connection between the Tarim and Tajik basins was disrupted between ca. 39 and 37 Ma and followed a northwestward younging trend (starting at ca. 41 in southern Tarim basin; Bosboom et al., 2014a) supporting a tectonic control by the growing Pamir (Fig. 6).

Sediment provenance is consistent with a recycled orogen and foreland basin setting as supported by the convex-upward shape (Van Hinte, 1978) of the post-40 Ma subsidence curve (Leith, 1985) for the Tajik basin (Fig. 7A). The late Eocene–early Oligocene regression in the Tajik–Tarim basins can thus be explained by coastal progradation owing to high ratio of sediment supply to basin accommodation at this location. In particular the transition from marginal marine gypsiferous facies to transitional and continental deposits with occasional paleosols (e.g., ZD section) observed in upper Eocene strata of the Tajik basin including the southern Tien Shan, is interpreted to represent deposition in a distal foreland basin. The up-section coarsening trend reflects progressive encroachment of the growing Pamir thrust belt. Synorogenic deposition, magmatic activity, and crustal thickening in the Pamir as early as 40 Ma are consistent with early Cenozoic radial thrusting in the Pamir (Bosboom et al., 2014c) and Paleogene shortening and magmatism in central Tibet (Kapp et al., 2005), suggesting significant crustal thickening and elevation in the region since the Eocene (Fig. 7B). High elevation in the Pamir by Eocene time is also supported by oxygen isotopic compositions of Eocene–Oligocene carbonates in the Tarim basin (Bershaw et al., 2012).

6. Conclusions

Regression of the Paratethys in Tajikistan occurred during the middle–late Eocene (~39 Ma). Our data combined with data from the Tarim basin in China show a northwestward migration of the shoreline between 41 Ma and 37 Ma, which is consistent with northward indentation and growth of the Pamir. Whereas sea level changes associated with global cooling and glaciations may have controlled Paratethys regression during the early Cenozoic, growth
of the Pamir has exerted a primary control on sediment supply and accommodation, depositional environments, and subsequent deformation in the Tajik–Tarim basins by ca. 40 Ma. Topographic loading by the Pamir was responsible for the formation of a foreland basin system including the Tajik depression and Tarim basin during the late Eocene. Combined with evidence of thick crust and active Cenozoic tectonics in the Pamir, this suggests significant elevation in the region which needs to be considered in discussions on aridity and monsoonal climate in central Asia. We suggest that the formation of high topography in the Pamir and the associated orographic barrier likely severed the seaward connection between the Tarim and Tajik basins and contributed to aridification of central Asian since ca. 40 Ma.

Acknowledgements

We acknowledge Miriam Cobianchi for her help in the analysis of nannofossils and Oleg Mandic for his aid in identification of marine bivalves. We thank Nikolai Ishuck for help in the field and Anatoly Isshuk, Oimahmadov Ilhomjon, Yunus Mamadjanov and Anor Nyyozov for help with permits and logistics. We thank Jay Chapman for help with drafting and discussions. Editor An Yin, John Bershaw and two anonymous reviewers are acknowledged for constructive criticisms. Funding was provided by National Geographic Society/Waitt Grants #W226-12, NGS grant #8442-08 to Kraatz, by Exxon Mobil Exploration to Carrapa, and by a National Natural Science Foundation of China Grant (41302144). We thank Mark Pecha and George Gehrels, at the Arizona Laserchron laboratory, for technical assistance.

Appendix A. Supplementary material

Supplementary material related to this article can be found online at http://dx.doi.org/10.1016/j.epsl.2015.05.034.

References


Fig. 7. (A) Subsidence analysis of the Tajik depression modified after Leith (1985). (B) Schematic cross section across the Pamir and Tajik–Tarim basin at ca. 40 Ma.


