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Asian monsoons and aridification response to Paleogene sea retreat and westerly shielding indicated by strong seasonality in Paratethys oysters

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Abstract

Asian climate patterns, characterized by highly seasonal monsoons and continentality, are thought to originate in the Eocene epoch (56 to 34 million years ago - Ma) in response to global climate, Tibetan Plateau uplift and the disappearance of the giant Proto-Paratethys sea formerly extending over Eurasia. The influence of this sea on Asian climate has hitherto not been constrained by proxy records despite being recognized as a major driver by climate models. We report here strongly seasonal records preserved in annual lamina of Eocene oysters from the Proto-Paratethys with sedimentological and numerical data showing that monsoons were not dampened by the sea and that aridification was modulated by westerly moisture sourced from the sea. Hot and arid summers despite the presence of the sea suggest a strong anticyclonic zone at Central Asian latitudes and an orographic effect from the emerging Tibetan Plateau. Westerly moisture precipitating during cold and wetter winters appear to have decreased in two steps. First in response to the late Eocene (34-37 Ma) sea retreat; second by the orogeny of the Tian Shan and Pamir ranges shielding the westerlies after 25 Ma. Paleogene sea retreat and Neogene westerly shielding thus provide two successive mechanisms forcing coeval Asian desertification and biotic crises.

Keywords: Eocene monsoon, aridification, Paratethys sea, Central Asia, seasonality, bivalves

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1. Introduction

Asian climate, governing the livelihood of billions of people, is characterized by high seasonality. In southeastern Asia seasons are expressed by high summer rainfall compared to winter in response to the archetypal monsoonal circulation. In contrast, central continental Asia records extreme seasonal temperature and minimal precipitation (Araguás-Araguás et al., 1998). The origin and past evolution of these seasonal patterns remain poorly constrained although they are key to deciphering their forcing mechanisms and to validate climate model predictions. To understand Asian climate, it is crucial to assess and quantify its past seasonality, in particular during the Eocene epoch (56 to 34 Myr ago), when high atmospheric pCO_2 levels kept global climate in a greenhouse state and the India-Asia collision shaped the paleogeographic features that would define Asian climate patterns (Zachos et al., 2001; Pagani et al., 2005).

During this epoch, the India-Asia collision resulted in the growth of the Tibetan Plateau and Himalayas. These orogenies are traditionally held responsible for the establishment of monsoons and desertification (Guo et al., 2002; France-Lanord et al., 1993) by creating orographic barriers as well as increasing atmospheric circulation through enhanced heat transfer from the plateau surface to the atmosphere (Molnar et al., 2010; Boos and Kuang, 2010; Wu et al., 2012; Liu et al., 2012). These environmental changes during Cenozoic have been called upon to explain major biotic events (Favre et al., 2015) such as the Mongolian Remodelling (Kraatz and Geisler, 2010; Fortelius et al., 2014) and the emergence of grassland and C4 plants (Edwards et al., 2010). Another competing forcing mechanism during this epoch is the strong global climate cooling from a greenhouse to an icehouse state. Models suggest that strong monsoonal circulation was maintained by warmer Eocene conditions (Licht et al., 2014) but subsequent global cooling led to Asian aridification and decreasing monsoonal intensity mostly due to diminished moisture transport (Dupont-Nivet et al., 2007; Licht et al., 2014). We focus here on the influence of the large epicontinental Proto-Paratethys sea that formerly covered Eurasia (Bosboom et al., 2014c). It is also recognized as a major driver by modelling studies suggesting that its presence would dampen the seasonal thermal contrast between the continent and surrounding oceans negating the possibility of intense Eocene monsoons (Ramstein et al., 1997; Zhang et al., 2007). Also the sea potentially provided an important moisture source transported by the westerlies into Asia (Dupont-Nivet et al., 2007; Zhang et al., 2012). The sea fluctuations and retreat may therefore have modulated Asian environments leading to desertification and increasing monsoonal circulation (Ramstein et al., 1997).

In principle, climate proxies of seasonality contrasts from the sedimentary records should enable to disentangle the respective contributions of forcing mechanisms suggested by climate models. If the sea indeed dampened the ocean-continent thermal contrast, a temperate climate with low seasonality would be expected. In addition, seasonality can be used to discriminate between monsoonal vs. westerly moisture sources because they have opposite precipitation patterns: monsoons are dominated by summer precipitation while westerlies are characterised by winter precipitation. Existing records of aeolian loess-like deposits (Licht et al., 2014), pedogenic stable isotope (Caves et al., 2015) and fossil pollen studies (Dupont-Nivet et al., 2008) point to monsoonal circulations with Asian interior aridity despite the Proto-Paratethys sea presence. However, no quantitative records of Eocene seasonality from this area have been hitherto produced due to the paucity of appropriate records and reliable methods to extract them.

To constrain seasonality, Bougeois et al. (2014, 2016) developed a geochemical high resolution multi-proxy approach (oxygen stable isotopes -δ^{18}O- and Mg/Ca elemental ratios) on pilot samples from fossil oyster shells of the Proto-Paratethys itself. Here we apply this approach to numerous specimens and complement this geochemical data with sedimentological paleoenvironmental analyses and a coupled atmosphere-ocean general circulation model -GCM- constraining independently oceanic and atmospheric temperatures, precipitation patterns and isotopic composition in the Proto-Paratethys region. Furthermore, the isotopic signatures of Paleogene to Neogene pedogenic carbonates are compared to the marine data to identify the evolution of moisture sources during sea retreat, regional uplift and global cooling.

2. Geological setting

This study focuses on the well-dated Proto-Paratethys sea sediments exposed today in the Tarim and Alai Valley basins over the foothills of the Central Asian (Pamir and Tian Shan) ranges (Bosboom et al., 2014c,a,b) (Fig. 1) that uplifted since the early Miocene (ca. 25 Ma Sobel et al. (2006); Zheng et al. (2015); Blayney et al. (2016)). In the early Eocene (ca. 55 Ma) the sea reached its maximum expansion, from the Tarim basin to the Mediterranean and linked Arctic and paleo-Indian oceans (Dercourt et al., 1993). After this, the sea retreated westward. It was barely reaching the Tarim basin towards the Late Eocene (ca. 37 Ma) and had shrunk to the Caspian sea's present position by the 34 Ma Eocene-Oligocene transition (Bosboom et al., 2014b). The retreat therefore likely results from tectonic deformations in response to the early Eocene India-Asia collision onset (Molnar et al., 2010). However, the eustatic drop associated with global late Eocene cooling that lead to the Antarctic ice sheet at the Eocene-Oligocene transition, probably also contributed to the sea retreat (Bosboom et al., 2014b).

3. Material and methods

3.1. Climatic model simulations

The model used to investigate the Eocene climate is the Hadley Centre General Circulation Model (HadCM3 Gordon et al., 2000) with isotope tracers incorporated (Tindall et al., 2009). The model resolution is 3.75 deg × 2.5 deg, with 19 vertical levels in the atmosphere and 20 levels in the ocean. The simulations used are as described by Tindall et al. (2010) and are based on Early Eocene boundary conditions (see supplementary material for details). However, we note that model boundary conditions for this time are subject to considerable uncertainty. Briefly, CO_2 was set to 1680 ppmv (6× pre-industrial levels) and was intended to represent the combined radiative forcing from all greenhouse gases (since CH_4 and N_2O were kept as pre-industrial). The land-sea mask and orography is described in Tindall et al. (2010) and was produced using similar methods to Markwick and Valdes (2004). Of particular relevance for our study is that Tibetan plateau is set to a maximum height of ~1500 m, the topography of the Tian Shan and Pamir are absent and Central Asia is covered by the Proto-Paratethys with a depth of under 100 m, and water exchange between the Proto-Paratethys and the Indian ocean is possible through a gateway wider than 15 latitudinal degrees. Exchange with the Arctic is more difficult as the Turgai Strait is only one gridbox wide and 80 m deep. As a result there can be no baroclinic flow and limited barotropic flow between the Proto-Paratethys and the Arctic. Globally the Eocene simulation was 14°C warmer and 20% more precipitation than a corresponding pre-industrial simulation (see supplementary material for more information) . Here we focus on gridboxes 37.5°N, 71.25°E and 40.0°N 63.25°E for ocean, and 40°N, 75°E for atmosphere, which are the closest area from field study since the position of the sites experienced no statistically significant latitudinal tectonic motion since the time of deposition (Bougeois et al., 2014).

3.2. Geochemical data for sclerochronology

To quantify seasonal variations of temperature and salinity of the Proto-Paratethys seawater, we applied geochemical incremental analyses on fossil oyster's ligamental area following the multi-proxy methodology developed by Bougeois et al. (2014, 2016).

Oyster sampling was performed with particular attention to: (1) good preservation of a ligamental area large enough for a high resolution infra-annual record through numerous years, (2) ensuring that specimens fossilized in living position in fully marine environments. We focus here to the well-dated Middle Eocene (Lutetian) species (Bosboom et al., 2014a,b,c) *Ostrea (Turkostrea) strictiplicata* and *Sokolowia* *buhsii*, which lived in subtidal environment (Fig. 2e,f) as attested by sedimentological analyses (see also supplementary material), and that have been shown to provide reliable Mg/Ca results (Bougeois et al., 2016). The oyster shells were sectioned perpendicular to their maximal growth axis and well polished before geochemical analyses. Cross sections of oyster shells reveal large numbers of distinct light and dark growth bands, especially well-expressed in the ligamental area resulting from the typical incremental growth of yearly dark-light couplets (Bougeois et al., 2014). Cathodoluminescence microscopy revealed the annual banding, attesting no diagenesis effect on the calcitic shells.

Mg/Ca analyses were performed with Laser Ablation-Inductively Coupled Plasma Mass Spectrometer (LA-ICP MS) at the Department of Earth Sciences in Utrecht University following two parallel transects perpendicularly to the growth direction. Upon checking the consistency of the two parallel transects, their results were averaged such that a single datapoint was obtained for each incremental position, then a moving average on 21 points is calculated to overcome ICP-MS noise (see Bougeois et al., 2014, 2016, for more details).

Microsample powders were drilled following growth layers every 100 to 120 µm using a Merchantek MicroMill then analysed for stable isotopes composition using a KIEL-III device coupled online to a Finnigan MAT-253 mass spectrometer at the Department of Earth Sciences in Utrecht University (KY01, AT04) and using a KIEL-IV device coupled to an Isoprime DI-IRMS at the Department of Earth Sciences in Pierre et Marie Curie University (AL02, MS05, AT20, AT19). Internal and international (NBS 19) standards were used for reproducibility. For both mass spectrometers, long-term analytical precision was better than 0.08‰ for δ^{18}O.

From all the specimens shown in Bougeois et al. (2016), we finally selected six specimens where reliable Mg/Ca and $\delta^{18}O_c$ were available. We show here only the part of the shells where both proxy were performed (all data sets are provided in supplementary material).

3.3. Geochemical data for carbonates sediments

Carbonates sediments (bioclastic grainstone to wackstone for marine sediments and carbonaceous pedogenic horizons for continental sediments) were sampled at Mine and Aertashi sections in Tarim Basin (China) for stable isotopes analyses (horizon level indicated in supplementary material). Continental sediments selected were carefully chosen from the finest granulometry (mudstones to siltstones) with carbonaceous matrix unaltered and devoid of secondary vein of calcite. To avoid effects of diagenesis, in laboratory we sampled the fresh core of samples.

After milling the sediments, we analysed the carbonate fraction using mass spectrometer SIRA 9 at

University Pierre and Marie Curie (Paris 6). Internal (white marble Marceau) and international (NBS 19) standards were used for reproducibility. Long-term analytical precision was better than 0.05‰ for δ^{13}C and 0.1‰ for δ^{18}O.

4. Eocene Central Asian seasonality and monsoons

4.1. Paleogene sedimentological facies analyses.

Paleogene sedimentological facies analyses have been performed throughout the Aertashi and Mine sections (Fig. 1) displaying alternation of marine and continental deposits recording several sea incursions and subsequent retreats (Fig. 3, 4 and detailed facies associations in supplementary material). Sedimentary facies and fossil assemblages of marine sediments (Fig. 2c-d) are characteristic of shallow marine environments between upper offshore to coastal plain, and typical of warm, carbonate-rich neritic ramps. Tidal flat environments indicate a calm and shallow epicontinental sea prone to record paleoclimate fluctuations. Continental deposits are indicative of flood plains, playa and sabhka environments (Fig 2a-b). Alternations of sandy fluvial channel-fills and flood plain red silty clays with nodular gypsum and desiccation cracks attest for strong seasonal contrasts testifying for successions of floods events and dessication periods typical of semi-arid climates as also indicated by existing marine microfossils and pollen data (Sun and Wang, 2005; Bosboom et al., 2014a,c). A modern analogue is provided by the Persian Gulf, which is directly connected to the Indian Ocean but protected in a wide gulf and subject to semi-arid conditions leading to playa and sabkhas hypersaline deposits (James and Dalrymple, 2010). To quantify the seasonality we explore model and proxy data in the following

4.2. Numerical simulations of Eocene climate.

Eocene climate (Fig. 5b) over the Proto-Paratethys sea region provided by the HadCM3 General Circulation Modelshows annual average sea surface temperatures (SST) of 23°C, with average seasonal cycle between 16°C and 34°C. Modelled δ^{18}O of sea water surface ($\delta^{18}O_{sw}$) values average 0.44‰ (SMOW) and, because ocean gridboxes are large and well mixed, show negligible seasonal variability. However, a higher variability is expected in the environments studied here because modelled air temperatures fluctuate largely between 7°C and 49°C (average of 26°C) and coastal areas are prone to seasonal water balance variations (Goodwin et al., 2001). Modelled precipitation in our study area are strongly seasonal peaking at 38 mm in January and reaching a 0.5 mm minimum in July. This pattern is consistent with previous Eocene model simulations (Zhang et al., 2012) and similar to modern conditions west of the Central Asian ranges (Bukhara site, Fig. 5) subjected to winter westerly precipitation. Stable isotope composition of precipitation ($\delta^{18}O_p$) is stable around -6‰ except for a significant increase during the warmest month with $\delta^{18}O_p$ =-1.7‰ in July. The model winter values are very far from isotopic composition of modern precipitation East and South of the Central Asian ranges (Araguás-Araguás et al. (1998), Hotan site, Fig. 5c). The general contrast between Eocene model and modern precipitation and isotopic seasonality suggests conditions have changed drastically since Eocene times in this area.

4.3. Eocene seasonality revealed by oyster shell geochemistry.

Along the ligamental areas of the shells, the growth bands show Mg/Ca and $\delta^{18}O$ periodic fluctuations, which are synchronized and anti-correlated (high values of Mg/Ca corresponding to low values of $\delta^{18}O$ and inversely). These variations with clear banding attest for a well-recorded seasonal pattern and no diagenetic alteration, as also supported by cathodoluminescence analyses (Fig. 6). The primary character of trace element and stable isotope values is attested by measurement reproducibility in these species, which display homogeneous values both within the same sedimentary horizon and in the different sections of Central Asia. According to Bougeois et al. (2014, 2016), we infer quantitatively temperature changes from the chemical oyster shell composition using the relationships calibrated in the modern oyster *Crassostrea gigas* (Mouchi et al., 2013):

$$T(^\circ C) = 3.77 \times \mathrm{Mg/Ca(mmol/mol)} + 1.88 \qquad (1)$$

The SST reconstructed from Mg/Ca are in excellent agreement with temperatures derived from the modelled HadCM3 (Fig. 5a,b). The seasonal temperatures amplitudes based on Mg/Ca (ΔSST=19°C) is slightly higher to the SST seasonality predicted from HadCM3 (ΔSST=18°C) and the annual averages (27±2°C according Mg/Ca vs 23±6°C according model) are comparable (details in supplementary material). Especially, Mg/Ca-based temperatures lay in-between the SSTs and the surface air temperatures predicted by HadCM3. These amplitudes between air and sea temperature are typically expected in these coastal environments (Goodwin et al., 2001) which further supports the validity of temperatures estimated with Mg/Ca.

We infer further paleoclimate information from the fossil $\delta^{18}O_c$ using the well established relationship for bivalves linking temperature T (°C), $\delta^{18}O_c$ (‰ VPDB) and $\delta^{18}O_{sw}$ (‰ VSMOW) (Anderson and Arthur, 1983):

$$T = 16 - 4.14 \times (\delta^{18}O_c - \delta^{18}O_{sw}) + 0.13 \times (\delta^{18}O_c - \delta^{18}O_{sw})^2 \qquad (2)$$

On first approximation a stable $\delta^{18}O_{sw}$ of 0.44‰ derived from the modelled HadCM3 (Fig. 5b) is used. The obtained average temperatures (28±2°C) are comparable to annual averages of modelled (23±6°C) and Mg/Ca (27±2°C) SST. However, temperature amplitudes reconstructed from $\delta^{18}O_c$ are considerably lower (ΔSST=9°C) than amplitudes of modelled and Mg/Ca SST. Given that $\delta^{18}O_c$ depends on temperature and $\delta^{18}O_{sw}$, this discrepancy is most likely due to stronger seasonal variability in $\delta^{18}O_{sw}$ compared to stable values in open water predicted by HadCM3.

These seasonal fluctuations in $\delta^{18}O_{sw}$ can be directly derived from equation (2) using the shell $\delta^{18}O_c$ and temperatures (T) deduced from Mg/Ca:

$$\delta^{18}O_{sw} \simeq \frac{T - 16}{4.14} + \delta^{18}O_c \tag{3}$$

Seawater oxygen isotope compositions thus obtained indicate high seasonal fluctuations with highest $\delta^{18}O_{sw}$ during summer months and ~3‰ lower values during winter (Fig. 6). These fluctuations are in full agreement with our sedimentological interpretations of oysters living environments at the epicontinental sea margin where runoff, precipitation and evaporation have a strong effect on $\delta^{18}O_{sw}$. This $\delta^{18}O_{sw}$ seasonality is also consistent with typical coastal environment influenced by dry summer conditions resulting in a negative water balance (increasing $\delta^{18}O_{sw}$ and salinity) contrasted with positive water balance during cooler and wetter winter months (decreasing $\delta^{18}O_{sw}$ and salinity) (Goodwin et al., 2001, 2010).

4.4. Interpretation of seasonality.

Our results show that the Eocene Central Asian summer climate was hotter than today and already arid despite the Proto-Paratethys sea presence (Fig. 5b). According to the model, Eocene seasonal air temperature amplitudes (ΔT~42°C) were higher than today (ΔT~32°C), and aridity was more sustained in summer with very low precipitation. As a moisture source, the Proto-Paratethys appears to have had little impact on local climate during summer. Most importantly, the high reconstructed summer temperatures imply that the shallow sea did not thermally buffer the Asian interior and delay the onset of monsoonal circulation, as suggested by previous models (Ramstein et al., 1997; Zhang et al., 2007). This may be attributed to overall warmer Eocene global climate imposing a stronger anticyclonic Hadley high pressure cell descending at these latitudes (25 to 45°N) over Central Asia (Zhang et al., 2012). It is also consistent with recent studies showing that high atmospheric pCO_2 levels had more impact on circulation than local paleogeography (Lunt et al., 2016). In addition, the emerging Proto-Tibetan plateau during this period (Molnar et al., 2010), even at low altitude, may have contributed to a stronger Foehn effect during summer months bringing warm and dry air into Central Asia (Fig. 7a). Our results are thus supported by recent model and proxy data suggesting modern-like Asian monsoonal circulation already established as early as Eocene times (Sun and Wang, 2005; Huber and Goldner, 2012; Licht et al., 2014; Caves et al., 2015).

In contrast, the observed summer aridity precludes previously proposed pre-Neogene low pressures and humid conditions north of the Tibetan Plateau, as this region would have been sufficiently shielded from Asian monsoon rains at this time and high pressures cell hence fixed to its north (Allen and Armstrong, 2012).

Furthermore, our results imply enhanced winter over summer Eocene precipitation, which is supported by climate model simulations suggesting a dominant westerly winter moisture source (Tindall et al., 2010; Zhang et al., 2012). Eocene winter air temperature was significantly warmer than today and the source of moisture unshielded by Central Asian ranges. The relatively high $\delta^{18}O_p$ and precipitation during Eocene winters can thus be interpreted as resulting from winter westerlies bringing moist air from the neighbouring Proto-Paratethys and adjoining seas (Fig. 7b). Reconstructed Eocene seasonality is actually comparable to modern conditions on the Central Asian ranges' western flank exposed to westerlies with enhanced winter precipitation (up to 85 mm/month - Fig. 5c, Bukhara site) (Araguás-Araguás et al., 1998). This sharply contrasts with modern climate patterns on the other side of the Central Asian ranges (Fig. 5c, Kashgar site). There, climate is hyper arid with maximum seasonal rainfall reaching only 12 mm/month in late spring and summer. The minimal moisture is typically recycled locally through groundwater evaporation or plant cover transpiration (Araguás-Araguás et al., 1998) resulting in strong seasonal variability off precipitation stable isotope (Fig. 5c).

Compared to Eocene, these regions are more arid today with a reversed summer/winter precipitation seasonality pattern. To understand the potential driving factors of these changes from Eocene to the modern climate patterns we investigate below the Eocene to Pliocene moisture evolution.

5. Eocene to Pliocene moisture evolution

To track the moisture composition through the Cenozoic, we analysed bulk carbon ($\delta^{13}C$) and oxygen isotopic compositions of Paleogene carbonates of Aertashi and Mine sections (Fig. 3 and 4), which are prone to reflect the isotopic composition of water in which they precipitated. These analyses include marine and pedogenic carbonates (Tab. **??** and **??**) and are complemented by the Neogene data provided by Kent-Corson et al. (2009).

Stable isotopes in continental vs. marine depostis are fundamentally different. In marine systems, ther is a subtantial influence of ice volume, temperature and especially in coastal area, a component of runoff on $\delta^{18}O$. In terrestrial systems, $\delta^{18}O$ is primarily controlled by the ratio of precipitation to evapotranspiration (Winnick et al., 2014). Similarly, $\delta^{13}C$ should have fundamentally different values in both marine and terrestrial systems, reflecting different sources of the carbon. The data are therfore interpreted separately.

The δ^{18}O from bulk marine limestones show a slightly decreasing trend from ca. -2 to -8‰ throughout the Late Paleocene to the Late Eocene. In contrast, terrestrial δ^{18}O strongly decrease from ca. -7 to -14‰ from the Eocene to the Miocene (Fig. 8).

δ^{13}C decreases from 6 to -5 ‰ in Eocene marine limestones. Then δ^{13}C increases to 3 ‰ from Late Eocene to Miocene continental pedogenic carbonates (details in supplementary material).

The Late Paleocene to Late Eocene decrease in marine δ^{13}C is consistent with an increase in runoff and a decrease in fully marine contributions due to the sea retreat. The Eocene to Neogene increase in terrestrial carbonates δ^{13}C may be partly related to the coeval mudstones to conglomerates lithologic changes (Kent-Corson et al., 2009). However, the rise is also consistent with regional aridification (Bosboom et al., 2014b; Sun and Wang, 2005; Quan et al., 2012) syggesting alternatively that it results from a combination of water scarcity increasing the δ^{13}C of plant matter (Suits et al., 2005; Diefendorf et al., 2010; Kohn, 2010) and a decrease in plant productivity (Caves et al., 2016) that would reduce the quantity of soil respired CO_2.

The δ^{18}O decrease in marine limestones since ca. 55 Ma likely reflects the retreating sea with a shift to more coastal environments increasingly affected by precipitation and runoff (Bosboom et al., 2014a). At the transition from marine to continental deposits associated with the sea retreat out of the Tarim Basin (ca. 37 Ma), overlapping marine limestones to continental carbonates δ^{18}O values suggest a gradual transition with continental precipitation being evaporated from the nearby sea. After the marine-continental transition and up to the Pliocene, the δ^{18}O decrease must be interpreted in terms of precipitation. These are most likely governed by westerly moisture sources given the predominant winter precipitation indicated by the seasonality data above. This corroborates the recet compilation of pedogenic and lacustrine carbonate δ^{18}O data across Central Asia also indicating that the westerlies were the dominant cource of moisure and therefore must have controlled aridification (Caves et al., 2015) Of the many factors that may have influenced the precipitation δ^{18}O decrease, the distance from the source and an orographic rain-shadow effect of the Central Asian ranges probably dominated compared to relatively small expected δ^{18}O decrease due to altitude and temperature changes of the site (Araguás-Araguás et al., 1998; Botsyun et al., 2016). Indeed this time interval corresponds to further westward sea retreat (Bosboom et al., 2014c,b) and regional uplift shielding the Tarim Basin from the westerlies (Sobel et al., 2006; Zheng et al., 2015; Blayney et al., 2016; Caves et al., 2016, 2017).

Finally, because the sea had already retreated back to the present Caspian Sea location after the Eocene-Oligocene transition (Bosboom et al., 2014c), most of the subsequent isotopic change must be attributed to orographic effects related to the Tian Shan and Pamir uplifts (ca. 25-15 Ma Sobel et al., 2006; Zheng et al., 2015; Blayney et al., 2016). In addition, decreasing δ^{18}O may results from a greater contribution of high-elevation precipitation ot the local water (Macaulay et al., 2016).

6. Conclusions

Our results reveal clear and cyclic geochemistry alternations in fossil oyster shells indicating an exceptional preservation suitable for climate proxy reconstruction. These records, in excellent agreement with sedimentology and numerical simulations, enable to constitute the first robust quantitative estimate of seasonality for this area with the following implications.

Despite the presence of the Eocene Proto-Paratethys sea, the Asian interior climate was semi-arid and strongly seasonal receiving dominantly winter moisture from the westerlies. Highly seasonal temperature contrasts indicate that the shallow sea did not have a strong dampening effect that may imply monsoonal circulation. This contrasts with previous modelling studies (Ramstein et al., 1997) but confirms recent regional evidence for strong Eocene monsoons (Licht et al., 2014).

The sea, however, provided moisture to Central Asia through westerlies during Eocene winters. Our results, thus suggest a two step aridification. The first one related to the Eocene to Oligocene westward Proto-Paratethys sea retreat and affecting central to eastern Central Asia (Bosboom et al., 2014a). The subsequent aridification associated with the early Miociene uplift of Pamir and Tian Shan affecting the regions east of these ranges shielding the westerlies and leading to enhanced aridification, recycled precipitation patterns and desertification of Taklamakan, Qaidam and Gobi regions. These two events are consistent with the documented paleo-wind patterns (Licht et al., 2016), and provide respectively a driving mechanisms for the generation of (1) Eocene aeolian loess-like deposits (Licht et al., 2014) in response to the sea retreat, and (2) Mio-Pliocene Loess (Nie et al., 2015) in response to Central Asian ranges orogenies. The past diminution of westerly rather than monsoonal moisture was thus more likely the governing factor of the aridification held responsible for major biotic crisis documented in this area (Kraatz and Geisler, 2010; Fortelius et al., 2014; Edwards et al., 2010).

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Figure and Table captions

Figure 1: Localisation of study area. Modern topographic map of the study area showing the main tectonic features and the localisation of the sampled sedimentary sections (AL: Alai Valley, 39.6°N, 72.4°E; MS: Mine, 39°51'N, 74°32'E; AT: Aertashi, 37°58'N, 76°33'E; KY: Keyliand, 37°27'N, 77°86'E). The position of the sites experienced no statistically significant latitudinal tectonic motion since the time of deposition (Bougeois et al., 2014).

Figure 2: Paleogene depositional environments. Nodular (**a.**) and massive (**b.**) gypsum deposits indicate playa, salinas and sabkha environments typical from semi-arid climate (alternation of floods events and dessication periods). Tidal flat with neap-spring tide alternations (**c.**) and littoral barrier with rippled bioclastic grainstone (**d.**) indicate a low energy carbonate ramp environment. Fossil oysters lived in subtidal zone where *O. (T.) strictiplicata* (**e.**) built bioherms (patch reefs) and *S. buhsii* (**f.**) stood isolated in blue marls with bryozoa, serpulids, echinoids (see frame), foraminiferas and fishes attesting for a more quiet open marine environment.

Figure 3: Sedimentary log of Aertashi section (facies associations are described in supplementary material). Alternation of marine and continental deposits and record several sea incursions and subsequent retreats. Associated carbonate geochemistry analyses (δ^{18}O, δ^{13}C, % in $CaCO_3$) are reported throughout the section.

Figure 4: Sedimentary log of Mine section (facies associations are described in supplementary material). Associated carbonate geochemistry analyses are reported throughout the section.

Figure 5: Seasonal data. Comparison between (a) Eocene proxy data (see details in Fig. 6) and (b) monthly data provided by climatic simulations. (c) Average of monthly modern air temperature and precipitation in Kashgar (China) from 1951 to 1993 (Baker et al., 1995) and in Bukhara (Uzbekistan) from 1982 to 2012 (www.climate-data.org) ; modern oxygen stable isotopic composition of precipitation in Hotan (China) (Araguás-Araguás et al., 1998).

Figure 6: Polished cross sections of *O. (T.) strictiplicata* (3 top samples) and *S. buhsii* (3 bottom samples) revealing annual growth bands (arrows indicate growth direction). Cathodoluminescence microscopy analyses (CL) show no diagenetic alteration. Grey bands correspond to dark bands in the shells which are built during the coldest months of the year. Black lines indicate main paths drilled for δ^{18}O analyses. Orange lines indicate transects followed by laser for Mg/Ca analyses. Mg/Ca is given in mmol/mol, $\delta^{18}O_c$ in ‰ VPDB, $\delta^{18}O_{sw}$ in ‰ SMOW, temperatures in ° Celsius. Distance is measured from the first drilled micro-sample for δ^{18}O. Temperatures are estimated from elemental composition (Mouchi et al., 2013) and Apparent temperatures from $\delta^{18}O_c$ (Anderson and Arthur, 1983), with a constant $\delta^{18}O_{sw}$ = 0.44‰. See main text for the calculation of $\delta^{18}O_{sw}$ from Mg-deduced temperature and $\delta^{18}O_c$.

Figure 7: Eocene paleogeographic maps of Asia showing the interpreted general summer (**a**) and winter (**b**) wind patterns 40 Ma ago, according to this study and previous numerical simulations (Huber and Goldner, 2012; Zhang et al., 2012; Licht et al., 2014). The descending branch of the Hadley cell is responsible for a broad and large band of semi-arid to arid climate (Zhang et al., 2012), which is intensified during summer months in Central Asia due to the Foehn effect induced by the emerging Tibetan plateau. In winter, aridity is less strong due to precipitation associated with the westerly winds over the Proto-Paratethys sea that were not yet impeded by the Pamir and Tian Shan.

Figure 8: Eocene to Pliocene stable isotopic composition (δ^{13}C and δ^{18}O) for Tarim Basin carbonaceous sediment from this study (Aertashi and Mine sections, see supplementary material) and Kent-Corson et al. (2009) data (Aertashi section). Crosses show averages and standard deviation for each time interval. Gray arrow shows the trend through geological times.

Table 1: Carbon (δ^{13}C in ‰ VPDB) and oxygen (δ^{18}O in ‰ VPDB) isotopic composition from marine and pedogenic carbonates in Aertashi section.

Table 2: Carbon (δ^{13}C in ‰ VPDB) and oxygen (δ^{18}O in ‰ VPDB) isotopic composition from marine and pedogenic carbonates in Mine section.