Timing and paleogeography of the Paleogene sea retreat from the Afghan-Tajik Basin, southwestern Tajikistan

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Abstract

Before the birth and isolation of the Paratethys by the collision of the Eurasian, Indian, African and Arabian plates, a vast amount of water connected the Central Asian basins, ranging from the Tarim Basin in present day western China to the eastern Mediterranean. This was a large shallow sea referred to as the proto-Paratethys. During the Eocene, the eastern margin of this sea showed a large westward shift, which happened by 5 transgressive and regressive cycles. Recent research in the Tarim Basin has shown that the second-last marine incursion took place during the Bartonian and the last and last marine incursion during the early Priabonian.

A logical next step would be to date the retreat of the sea from the Afghan-Tajik Basin, which is situated to the west of the Tarim Basin. This would give a better picture of the extent of this retreat, which would provide more insight in the paleogeography of Central Asia during the late Eocene, and on the shift from this proto-Paratethys to the Paratethys Sea. Also this could shine a light on the possible causes and implications of this sea retreat. This was done in this study by magnetostratigraphic analyses of the continental deposits directly following the last marine sediments at four different locations in the Afghan-Tajik Basin in southwestern Tajikistan. It was chosen to focus the paleomagnetic investigation on the continental deposits as previous studies on similar marine sediments did not give reliable results.

Based upon lithostratigraphic correlations of the sections in the Afghan-Tajik Basin with the sections of the Tarim Basin, it was found that the last 2 transgressions found in the Tarim Basin were also present in the Afghan-Tajik Basin. This is a good indication of the retreat from the two basins being part of the same process. Ás the last sea retreat from the Tarim basin was during the early Priabonian, the last retreat from the Afghan-Tajik Basin is also likely to have taken place during the Priabonian. The sampled sections however, which were on top of the last marine sediments have ages of most likely Oligocene age. This suggests that the disconformity found in the Tarim Basin at the Eocene-Oligocene transition (EOT), associated with a major sea level drop, is also present in the Afghan-Tajik Basin. This would then give the last retreat from the Afghan-Tajik Basin a Priabonian age between ~37Ma and ~34Ma, the age of the last retreat from the Tarim Basin and the EOT. There was also looked at the rotations, and it was shown that the sections had undergone a counterclockwise rotation between 20° and 30°.

The retreat is likely to be caused by a combination of eustatic sea level changes during the late Eocene, and early uplift processes of the Pamir mountain range as shown by a rotational analysis done in this study. It has been suggested that the presence of the large epicontinental sea in Central Asia was a major contributor to the moisture on the Asian continent. As shown in this thesis, during the final sea retreat the eastern margin of the sea shifted over 500 km to the west, which makes it reasonable to suggest that this has had a great impact on the moisture supply to the Asian continent.

Keywords: Afghan-Tajik Basin, Paratethys Sea, Tarim Basin, EOT, Paleogene, Eocene, Central Asia, Paleogeography

Introduction

Often it has been suggested that the formation of the Tibetan Plateau, which has been formed by the Indo-Asia collision, is the most important factor in changing the Asian paleoclimate. The uplift of this plateau is said to be responsible for changes in atmospheric circulation models across the Asian continent, which caused major aridification (Boos and Kuang, 2010; Graham et al., 2005; Kent-Corson et al., 2009; Kutzbach et al., 1989; Prell and Kutzback, 1992; Ruddiman and Kutzbach, 1989; Sun and Wang, 2005). However, previous work by Garzione et al. (2005), Graham et al., (2005), Kent-Corson et al. (2009), Ramstein et al. (1997) and Zhang et al. (2007), showed by using general circulation models and by performing isotope analyses that the big-scale paleoclimatic changes could also relate to the redistribution of the land-sea thermal contrast, caused by the westward movement of an epicontinental sea which covered major parts of the Eurasian continent.

This shallow sea (referred to as the Tajik, Tarim or Turan Sea) was present in Central Asia from the early Cretaceous and during the Late Cretaceous and Paleogene it even covered parts of the present-day Tarim Basin in western China. It was part of the western Tethys Ocean and connected the different basins in Eurasia, before the formation of the Alpine-Himalaya collision belt in combination with global sea-level lowering caused the sea to isolate as the Paratethys Sea (Popov et al., 2004; Burtman, 2000; Burtman et al., 1996; Lan and Wei, 1995; Tang et al., 1989).

Integrated bio-magnetostratigraphic research has shown that the second-last major western retreat of the sea in the southwest Tarim Basin took place around ~41 Ma (base C18r), during the early Bartonian (Bosboom et al., submitted). This is close to the age of a major aridification step in the Xining basin along the northeastern Tibetan plateau, which has been dated at ~41 Ma (chrons C19n-C18r) (Abels et al, 2011; Bosboom et al., submitted). The last retreat of the sea from the Tarim basin was dated as latest Bartonian-early Priabonian (base C17n.3n-base C16n.1n) (Bosboom et al., submitted), this retreat is concomitant with an aridification step at ~37.1 Ma (top C17.1n) This shows that the presence of the sea was most likely responsible for the supply of moisture to large parts of the Asian continent.

The long-term westward retreat of the sea from Central Asia and its isolation as the Paratethys Sea following this retreat are still badly understood however. For this reason the project of which this thesis is part has investigated the age and paleogeography of the sea in Central Asia for a couple of years already, and after past fieldworks in the Alai Valley and Ferghana Basin in southern Kyrgyzstan and the Tarim Basin in western China, the next goal is the Afghan-Tajik basin in southwestern Tajikistan. The sea reached this basin during the early Cretaceous and after a series of transgressions and regressions it retreated during the Oligocene (Brookfield and Hashmat, 2001; Burtman, 2000; Burtman and Molnar, 1993; Burtman et al., 1996). This process is poorly constrained however and the current stratigraphic framework does not allow correlation between the recognized marine transgressions and regressions across Central Asia. The implementation of the Afghan-Tajik basin in this stratigraphic framework will help to understand its paleogeographic evolution through time, allowing a correlation with regional variations in tectonics, paleoenvironments and global changes in sea-level and climate.

Hence, the aim of this MSc. thesis is to date the last sea retreat from the Afghan-Tajik Basin in southwestern Tajikistan. This is done by magnetostratigraphic sampling and interpretation of the continental sequences directly following the last marine deposits at four different locations. A correlation is made between the sediments at the sampled locations and previously sampled locations by Bosboom et al. in the Ferghana Basin and Alai valley in Kyrgystan and the Tarim Basin in China. Accurate dating of the retreat and the correlation of Paleogene sediments in the Afghan-Tajik to other Central Asian basins, allows to constrain the paleogeography, causes and implications of the sea retreat.

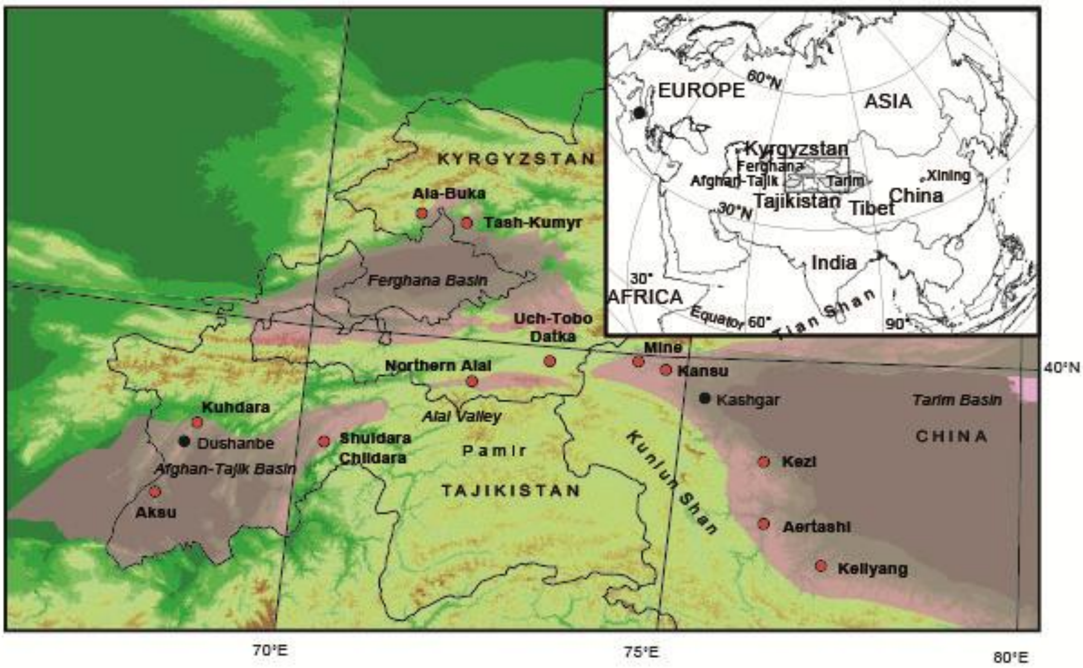


Figure 1 **Overview map of the area, with the Afghan-Tajik Basin in the west and the Tarim Basin in the east. Note that these basins are nowadays divided by the Pamir mountain range, but previously were connected . Both the sampled sections from this research as well as those from previous studies in the Tarim Basin and Ferghana Basin are indicated. Insert shows position on a global scale. (Image modified after Bosboom et al., submitted)**

Geological setting

The area investigated forms part of the Afghan-Tajik Basin, a large sedimentary basin covering parts of Uzbekistan, southwestern Tajikistan and northeastern Afghanistan. The basin has undergone some marginal overthrusting from the Tian Shan in the north, along the south Ghissar fault. It is overthrusted in the east, along the Darvaz fault by the Pamirs and in the south by the Hindu Kush along the Ishkashym fault zone. In the west, the Afghan-Tajik basin grades into the Amu-Darya Basin on the Turan plate (Brookfield and Hashmat, 2001; Nikolaev, 2002).

The first phase in the development of the basin was caused by Triassic rifting. The first sedimentary infill, which is directly overlying the Paleozoic basement, consists of Late Triassic to Middle Jurassic coal-bearing deposits which are of a mixed marine and continental origin. On top of that are Upper Jurassic marine carbonates and halokinetic salt deposits and Early Cretaceous red beds (Nikolaev, 2002).

The Paratethys Sea reached the Afghan-Tajik basin during the Albian and reached the Tarim Basin in the Early Cretaceous through the Alai Valley (Brookfield and Hashmat, 2001; Burtman, 2000; Burtman and Molnar, 1993; Burtman et al., 1996; Nikolaev, 2002). Five transgressions and regressions have been recognized in the southwest Tarim Basin, which are characterized respectively by sub- to intertidal facies (shallow marine carbonate platform and tidal flat deposits including light-colored limestones with typical fossil assemblages) and intra- to supratidal facies (lagoonal and tidal flat deposits including massive gypsum beds and reddish-brown gypsiferous mudstones). (Burtman, 2000; Burtman and Molnar, 1993; Tang et al.,

1992) The last two major sea retreats from the paleodepocenter of the southwest Tarim Basin, identified as the second-last and last transgression by Bosboom et al. (submitted) with the use of magnetostratigraphy and biostratigraphy, occurred in the late Lutetian and early Priabonian.

The complete marine sequence in the Afghan-Tajik Basin has an estimated thickness of over 3.000 m in the center (Brookfield and Hashmat, 2001; Burtman, 2000; Burtman and Molnar, 1993; Burtman et al., 1996; Nikolaev, 2002). The final transgression from Central Asia is poorly constrained to Oligocene time. The molasse deposits on top comprise fine-grained continental deposits with gypsum intercalations. According to sedimentological, stable isotope, provenance, thermochronology, paleomagnetic and backstripping data (Thomas et al., 1994; Yin et al., 2002; Yang and Liu, 2002; Burtman, 2000; Yin et al., 2002; Bershaw et al., 2012; Amidon and Hynek, 2010; Sobel and Dumitru, 1997) the thrusting and exhumation of the Pamir mountain range initiated somewhere between the middle Eocene and the early Miocene.

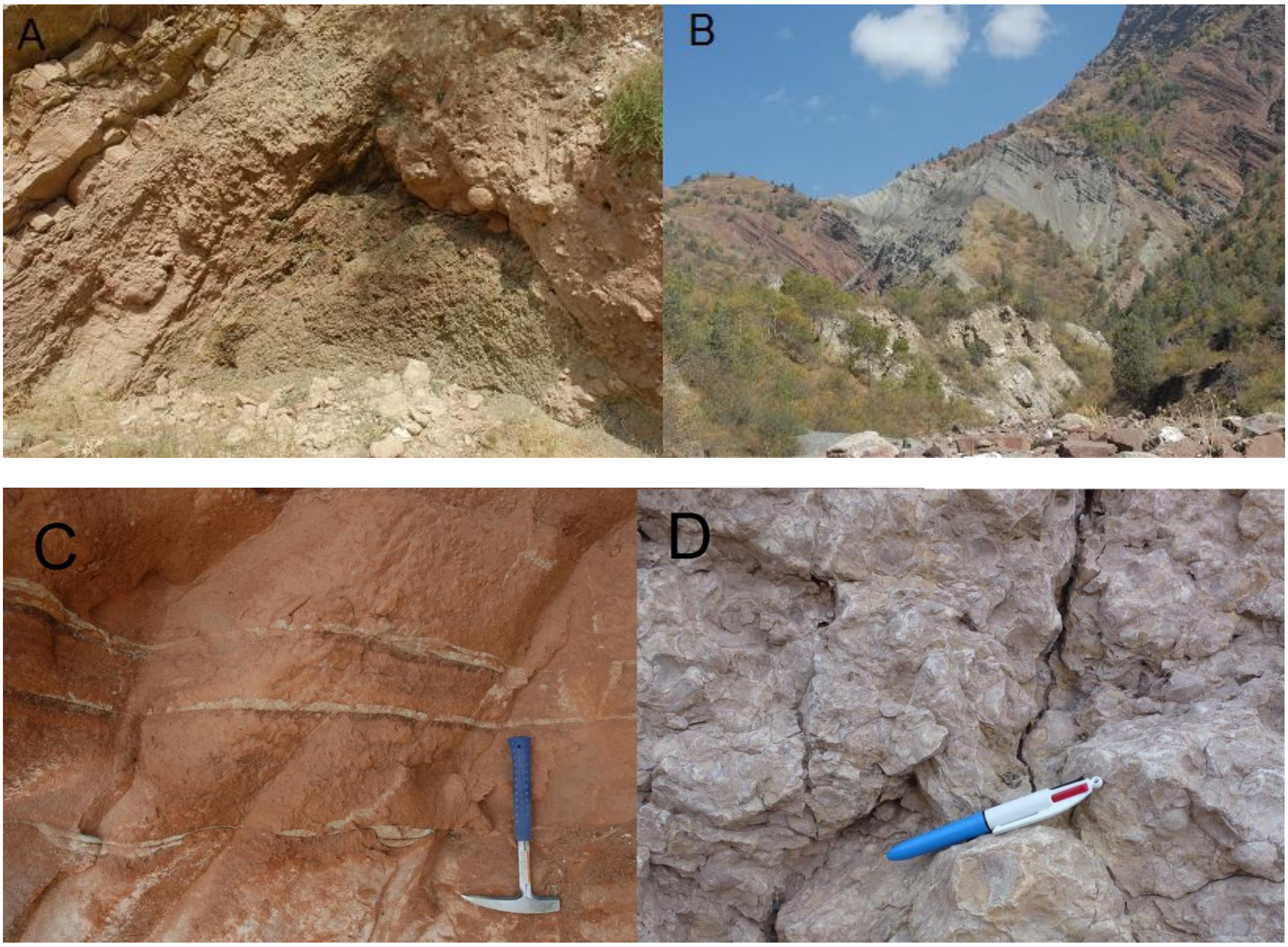


Figure 2 Outcrop examples from the Afghan-Tajik Basin. Fig.. A shows the fluvial, continental deposits at the Aksu section after the last sea retreat. Fig.. B shows an overview from the Shuldara section with a clear distinction between the marine and continental deposits. Fig. C. shows a continental bed from the Aksu section and Fig.. D shows a marine shellbed from the Aksu section.

Lithostratigraphy of sampled sections

In this study, the nomenclature of Dzahlilov et al. (1982) for the Paleogene formations in the Afghan-Tajik Basin is used. In chronological order, the formations in the Afghan Tajik basin are as follows, beginning from the K-T boundary; Akdjar, Tabakcha, Arukfan, Karatag, Givar, Jukar, Beshkent, Tochar, Kushan, Shanglak, Shurysay and Kamoli.

The first sampled section is the Aksu section (38,12° N, 68,58°'E), around 50 km southwest of Dushanbe. The second section is the Childara section (38,78°'N, 70,31°'E), around 150 km east of Dushanbe. The Shuldara section (38,80°'N, 70,35°'E) is located close to the Childara section. The last sampled section is the Kuhdara section (38,64°'N, 68,89°'E), located just to the north of Dushanbe.

The correlation between the four studied sections and the sections previously described by Bosboom et al. (2011) in the southwestern Tarim Basin and the Ferghana Basin and Alay valley in Kyrgyzstan (Fig. 1), was done by lithostratigraphic and biostratigraphic comparison between these sections and with the use of the studies of Burtman (2000) and Dzhalilov et al. (1982) The stratigraphic thicknesses were measured on the decimeter scale with the use of a Jacob's staff.

The Aksu section outcrops in a small river stream incised valley and has fairly constant bedding plane orientations, with strikes varying between 190° and 200° and dips around 70°. The section starts with thin bedded marl and limestone layers. These layers are characterized by the occurrence of shells, miliolids, gastropods, brachiopods and some oysters. Sedimentary structures found in these beds include planar lamination and carbonate hardgrounds. The marine sequences are correlated to the Jukar and lower Tochar formations. The marl and limestone beds with bioturbation and bivalves seem analogue to the Kalatar and Wulagan formations in the Tarim Basin (Bosboom et al., submitted), and are therefore possibly related to the second-last marine transgression. After the evaporate layer there is poorly exposed interval of around 150 m comprising alternating reddish and green mudstones which are believed to be the upper Tochar, Kushan and Shurysay Formations based upon comparison to Dzhalilov et al. (1982) and probably equivalent to the fine-grained and less resistant deposits Bashibulake Formation in the Tarim Basin (Bosboom et al., submitted). After this, a small green sandstone layer marks the start of the continental succession of the Shurysay Formation, which is our target for paleomagnetic sampling. This sequence is composed of alternating beds of reddish sands, silts and muds. The sand beds are characterized by cross-bedding and channels. At the beginning of this sequence there is a relatively even distribution of sandy and muddy beds, these are interpreted as fluvial and lacustrine deposits, which show similarities with the molasses assemblage described by Nikolaev (2002), with the sands being mostly fine-grained. Towards the end of the section the sand beds are getting thicker and coarser, eventually dominating the stratigraphy. (Fig. 3)

The Kuhdara section is just as the Aksu section sampled and described at the incision of a small stream. It is relatively well-exposed, although there are some longer areas without good exposure. The bedding plane orientation is fairly constant with strikes varying between 90° and 100° and dips between 35° and 45°.This section starts with thinly bedded limestones with an occasional evaporate layer. These beds are characterized by hardbeds and the occurrence of shells, bioturbation and oolites. By lithostratigraphic and biostratigraphic comparison to the studied marine sequences at the Aksu section and in the Tarim Basin (Bosboom et al., submitted) this marine sequence was interpreted as correlating to the Jukar formation. This has a similar appearance as the Jukar formation at the Aksu section, and also to the Kalatar and Wulagen formations in the Tarim Basin (Bosboom et al., submitted), therefore this is also interpreted as the second-last transgression. Higher in the sequence, the deposits go from a mostly carbonate nature to more siliciclastic sediments with some cross-bedding and wave-ripples, indicating a shift to a more near-shore, continental environment. These beds seem to correlate to the Beshkent formation as described by Dzhalilov et al. (1982). Hereafter the deposits become completely continental, consisting of thin-bedded alternations of dominantly red fine sands and silts with some thin, black sandstone beds containing up to medium-sized mica grains. Some of the sand layers show cross-bedded channel structures. These deposits are interpreted as belonging to the Tochar formation. This is followed by a relatively long poorly exposed interval with some cross-bedded red sandstone layers. The sequence continues with thin-bedded alternations of muds and sandstones, with cross-bedding and through cross-bedding. These beds are interpreted as the Kashan and Sanglak formations as described by Dzhalilov et al. (1982). Near the end of the succession the sands dominate and more often thick sand beds occur, which are of the Shurysay formation. (Fig.4)

The Childara section was logged and sampled along the road from Childara to Tavildara. The bedding plane orientations are between 200° and 230°, the dips are steepening in the younging direction from 40° to 75°. This section is less straightforward to correlate into the existing framework of Central Asian basins and to the other sections in the Afghan-Tajik Basin. This section is not directly coupled to a marine phase, but the sampled sedimentary succession probably represents the continental red-bed sequence overlying the last marine incursion. The lithologies consist of alternating thin layers of reddish and brownish muds and fine sandstone layers. Towards the end of the succession the rocks become harder and seem to be slightly metamorphosed. Alternating red fine sand and mud beds is a feature also seen in the Shurysay formation at the Aksu and Kuhdara sections, and therefore it indeed seems reasonable to assume that the Childara section is younger than the last marine interval. (Fig. 5)

The Shuldara section was logged at an outcrop just north of the road from Childara to Tavildara. The section starts with thinly alternating mud, sandstone and marl beds which are characterized by wave ripples, bioturbated shell fragment. This formation ends with a relatively thick mudstone bed followed by an evaporate layer. This lower part is correlated to the Beshkent and lower Tochar formations and followed by roughly 200 meter of poorly exposed section with some sandstone and siltstone beds with cross-bedding, through-cross-bedding, rootlets and bioturbation. At the end of the section the exposure gets better and thick bedded marls and mudstones are visible. These beds are interpreted as the upper Tochar, Kushan, Shanglak and Hissarak formations, and are similar to the calcareous mudstones and marls as described by Bosboom et al. (submitted) for the last transgression. (Fig. 6)

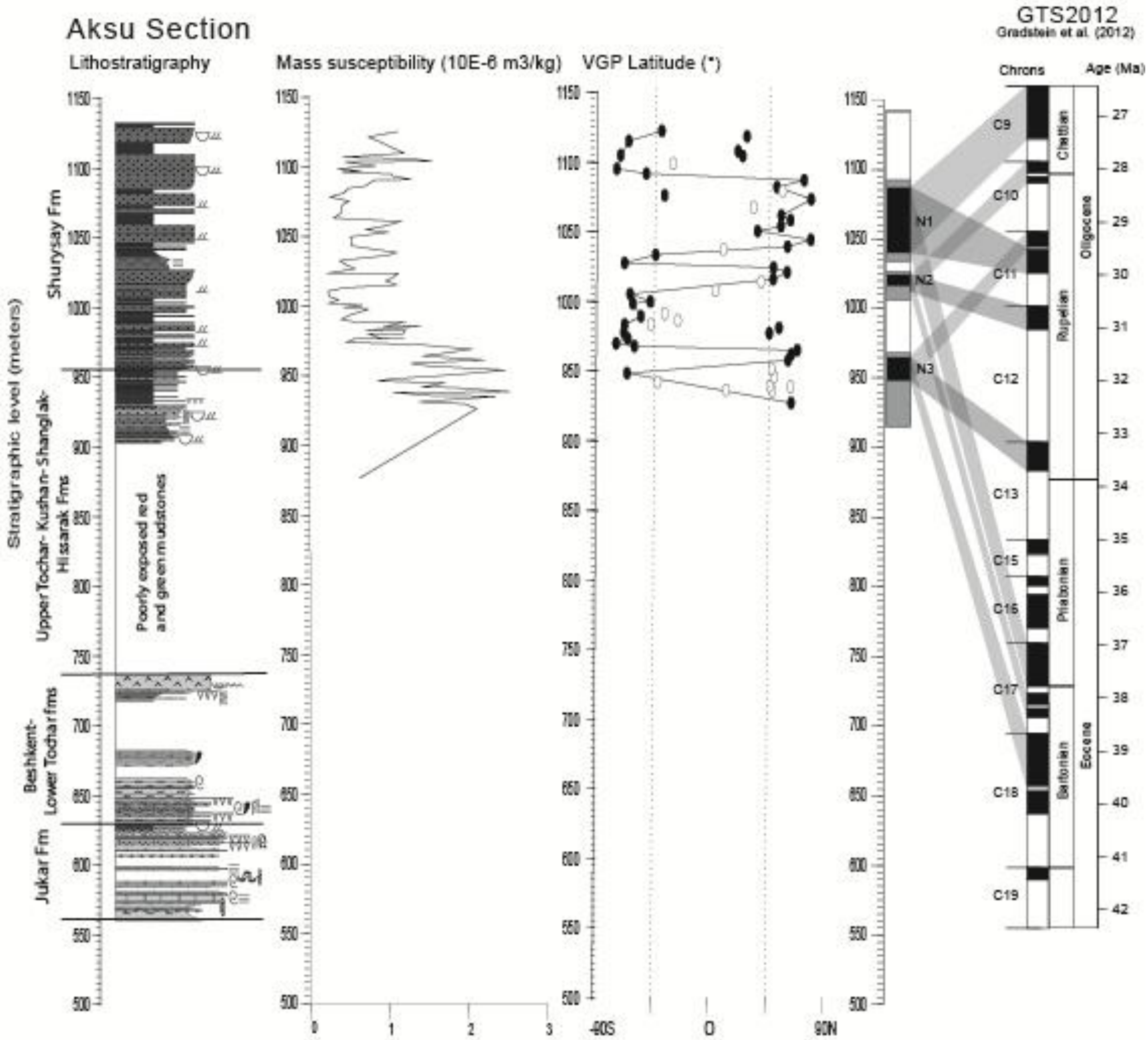


Figure 3 **The Lithostratigraphy, mass susceptibility, VGP latitude and corresponding polarity zones correlated to the Geological Time Scale by Gradstein et al. (2012) for the Aksu section. Open points in the VGP latitude Fig.ure indicate the samples are not within the 45° polarity range, and therefore are rejected. Closed points are accepted within the 45° polarity range and therefore used for polarity correlation. Single points of the opposite polarity in a polarity interval are neglected.**

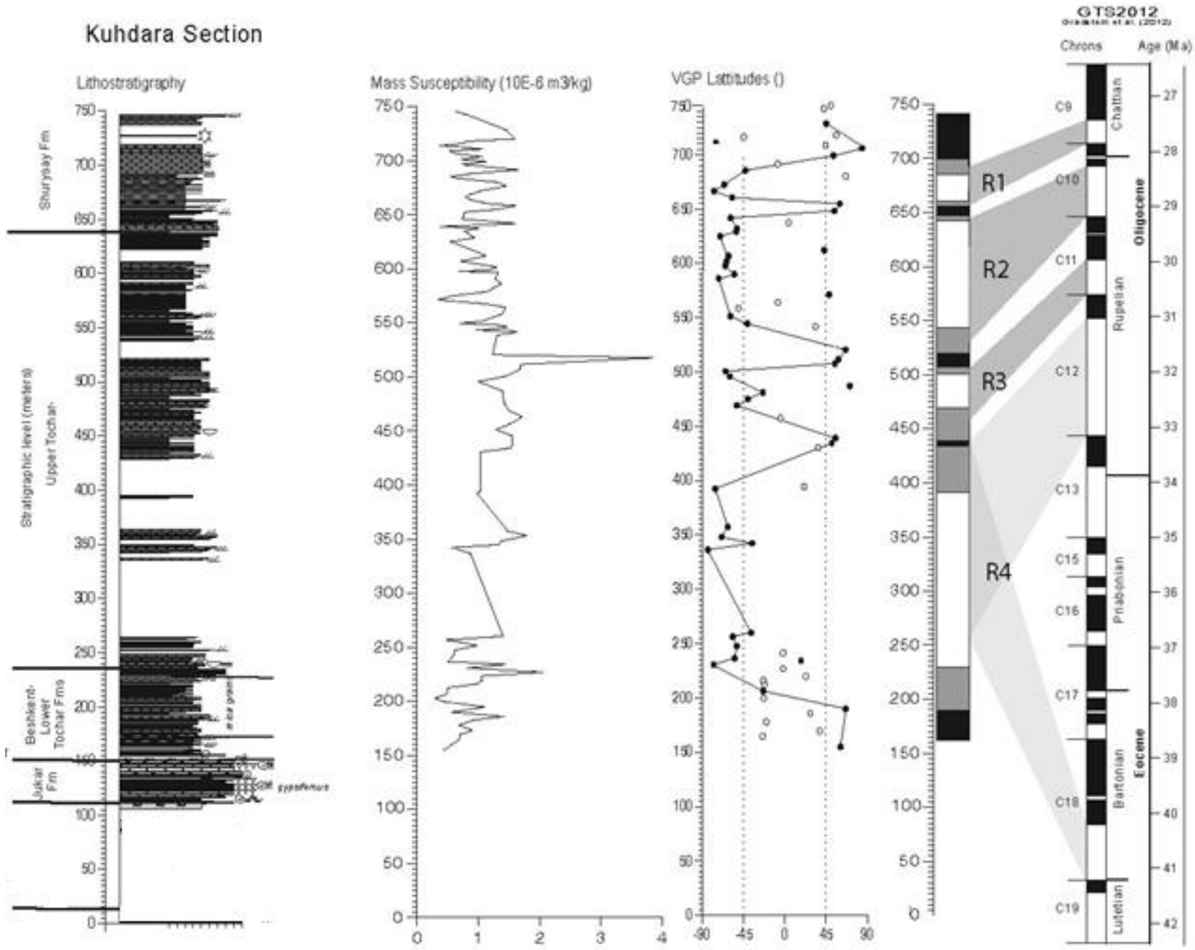


Figure 4 **The lithostratigraphy, mass susceptibility, VGP latitude and corresponding polarity zones correlated to the Geological Time Scale by Gradstein et al. (2012) for the Kuhdara section. Open points in the VGP latitude Fig.ure indicate the samples are not within the 45° polarity range, and therefore are rejected. Closed points are accepted within the 45° polarity range and therefore used for polarity correlation. Single points of the opposite polarity in a polarity interval are neglected.**

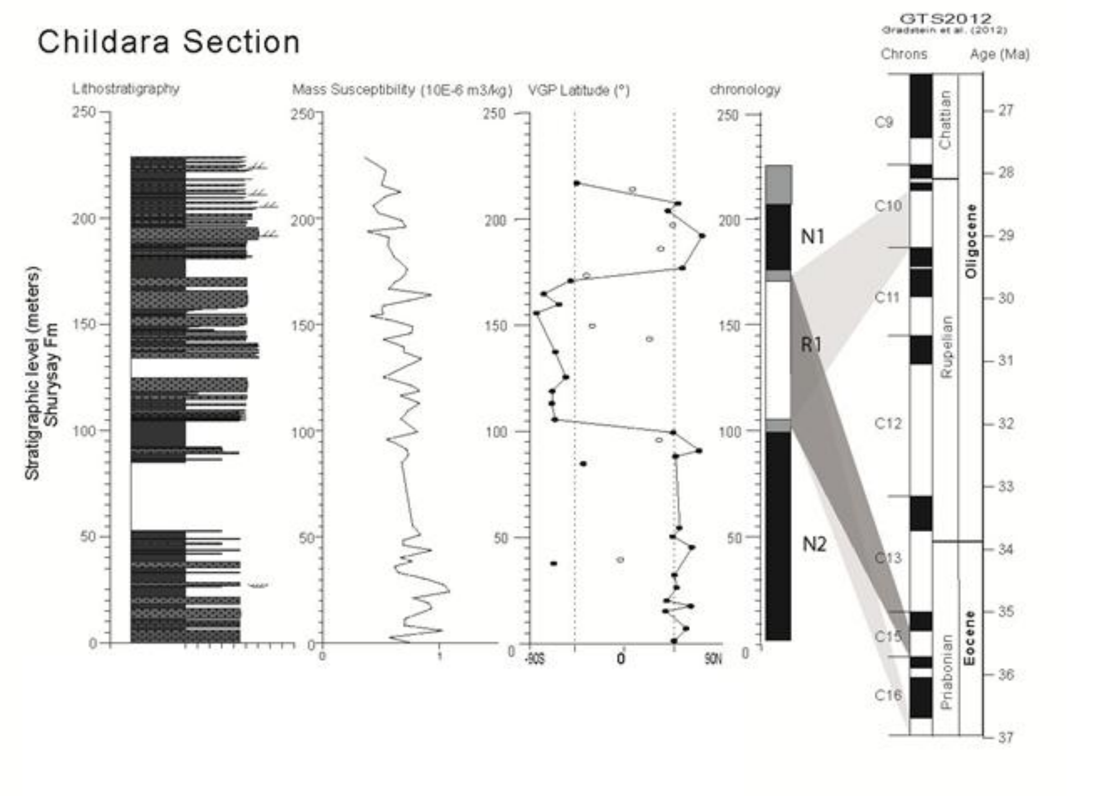


Figure 5 **Correlation of the lithostratigraphy, mass susceptibility, VGP latitude and corresponding polarity zones correlated to the Geological Time Scale by Gradstein et al. (2012) for the Childara section. Open points in the VGP latitude Fig.ure indicate the samples are not within the 45° polarity range, and therefore are rejected. Closed points are accepted within the 45° polarity range and therefore used for polarity correlation. Single points of the opposite polarity in a polarity interval are neglected.**

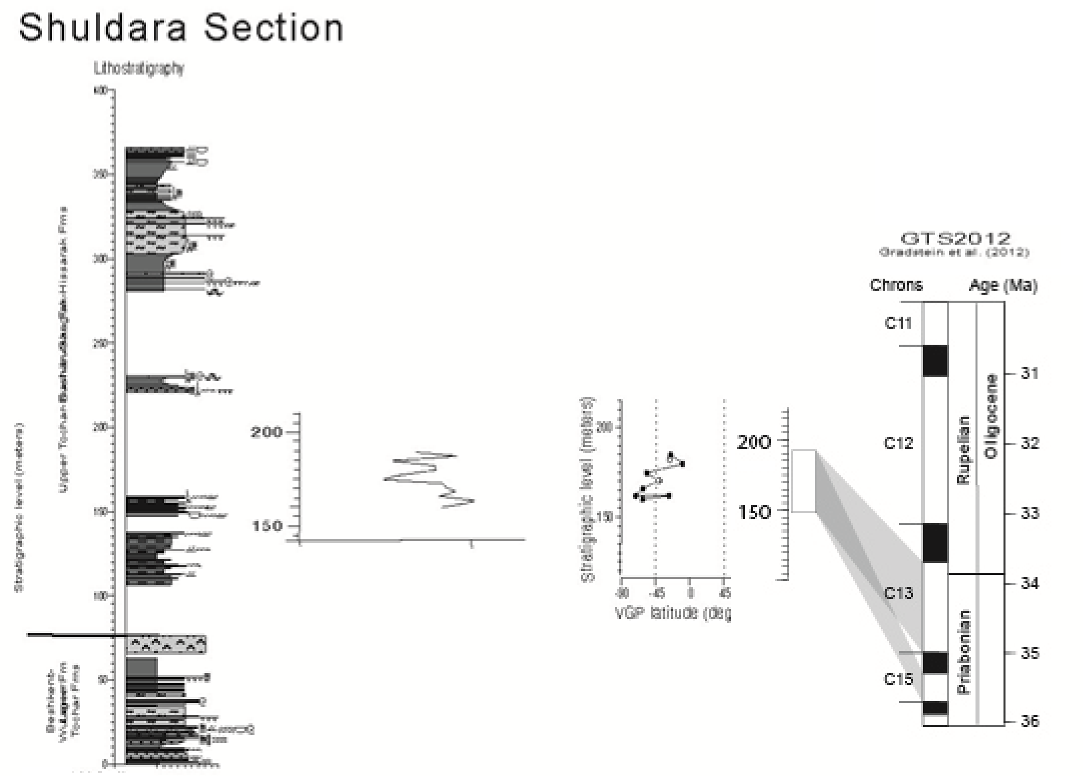


Figure 6 Correlation of the lithostratigraphy, mass susceptibility, VGP latitude and corresponding polarity zones correlated to the Geological Time Scale by Gradstein et al. (2012) forthe Shuldara section. Open points in the VGP latitude Fig.ure indicate the samples are not within the 45° polarity range, and therefore are rejected. Closed points are accepted within the 45° polarity range and therefore used for polarity correlation. Single points of the opposite polarity in a polarity interval are neglected.

Paleomagnetism

The paleomagnetic sampling was mostly aimed at the first continental successions after the marine sediments because previous research on sediments of these kinds in the Tarim Basin (Bosboom et al; submitted) showed remagnetization in the present-day field for the marine samples. For the paleomagnetic sampling at the Aksu, Childara, Shuldara and Kuhdara sections we used a battery-powered portable drill. The samples were drilled at a resolution ranging from 1 to 5 meters and afterwards orientated with a magnetic compass. At the paleomagnetic laboratory "Fort Hoofddijk" of the Faculty of Geosciences from Utrecht University the samples were first cut into cylinders of approximately 2 cm in length and afterwards analyzed in the shielded parts of the laboratory.

Rock magnetism

The first analytical step was to determine the rock magnetic properties of the collected samples and to find out what would be the best procedure for thermal demagnetization. First all individual samples were measured for their susceptibility on a KLY-2 susceptibility bridge at room temperature. (Fig. 3, 4, 5 and 6) After that the rocks were analyzed for their rock magnetic behavior. To do this, representative samples of the characteristic different lithologies were crushed and powdered and measured on a Curie balance (Mullender et al., 1993). For this four different representative samples were taken. From the Aksu section, sample AS17 was taken, a red mud. Sample CD44 was taken from the Childara section, a red fine sand. From the Kuhdara section, KD67 and KD111 were taken, which are respectively a yellow-reddish mud and a blue marine mud (Fig. 4).The AS17 and CD44 sample show magnetic characteristics which would indicate hematite as being the main magnetic carrier. The KD67 sample does not really show sudden drops in magnetic intensity. The KD111 sample shows the distinctive peak which indicates iron sulphides as being the magnetic carriers. To investigate the decrease in magnetic susceptibility with increasing temperatures the KLY-3 kappabridge was used. The results are plotted in figure 9.

Thermal demagnetization

Based upon the rock magnetic analyses, a representative selection of samples was made for thermal demagnetization in a shielded oven by using 19 temperature steps, between 20°C and 700°C for the continental 'red'samples and 29 temperature steps for the 'blue' marine samples, varying between 5 and 100˚C. At each temperature step the remanent magnetization was measured using a 2G enterprises DC SQUID cryogenic magnetometer. After removing the overprint component (from mostly the Childara section), most trajectories of the characteristic remanent magnetization (ChRM) show linear decay towards the origin at temperatures which are in agreement with the rock magnetic results from the previous paragraph (see Fig. 8).

For the Aksu section, most samples showed a decrease towards the origin between roughly 400 and 700 °C, this would indicate hematite as being the most important magnetic carrier. Most samples from this section were of reasonable quality, most had a clear polarity, less than a half of them however had both a clear polarity and showed a distinctive direction. Around a quarter of the samples showed no clear polarity and direction. For a lot of the samples the stability was varying a lot, not decaying to the origin in an approximate straight line. The magnetic intensities also tend to change a lot, with intensities for this section ranging between 500×10^{-2} mA/m and 10.000×10^{-2} mA/m. The red mud samples gave the best results and the highest magnetic intensities of around 10.000×10^{-2}, the sand samples, especially the coarser samples gave varying results and much lower intensities.

The Childara and Shudara sections are relatively similar in character, with most samples having a clear direction and polarity, as both sections are geographically close by and are composed of fine red sand and mud alterations. For the Childara section, the samples decay towards the origin between roughly 450 and 700°C, which also indicate that hematite is the main magnetic carrier. These samples are all relatively stable and have magnetic intensities mostly between 1500×10^{2} mA/m, and 5000×10^{2} mA/m with some a lot higher or lower. These intensities have around the same values as comparable samples from the Aksu and Kuhdara section. The Childara section has a lot of samples with an overprint between 150 and 450 °C.

The Kuhdara section is divided into a continental and a marine part. The continental part is generally of a good quality with around half of the samples showing both clear polarity and direction. The samples tend to decay towards the origin between roughly 250 and 685 °C, which also indicates hematite as being the most important magnetic carrier. Magnetic intensities are below 10.000×10^{2} mA/m. Muds generally show higher intensities than sands. Intensities are comparable to the other sections. The marine part of this section shows different behavior. These samples are unstable and tend to decay between 100 and 400°C, confirming iron sulfides are the main magnetic carriers. These samples have low magnetic intensities with values between 100×10^{2} mA/m and 500×10^{2} mA/m. For most of these samples it is hard to indentify a clear polarity and direction.

ChRM analyses

With the application of principal component analyses (Kirschvink, 1980) the ChRM directions were calculated from orthogonal plots. A minimum of four temperature steps was used for the line-fits and only in some exceptional cases in which all directions were clustered; the line was forced through the origin. Most of the line-fits had a maximum angular deviation (MAD) below 15˚, but if the polarity could be clearly recognized, MADs of up to 30˚ were accepted. The next step was to calculate Virtual Geomagnetic Pole (VGP) latitudes from the obtained ChRM directions. Outliers and transitional directions lying over 45˚ from the mean were systematically discarded from the data (Deenen et al., 2011). The remaining directions were corrected for bedding tilt, and the mean normal and reversed ChRM directions were calculated (Fisher, 1953).

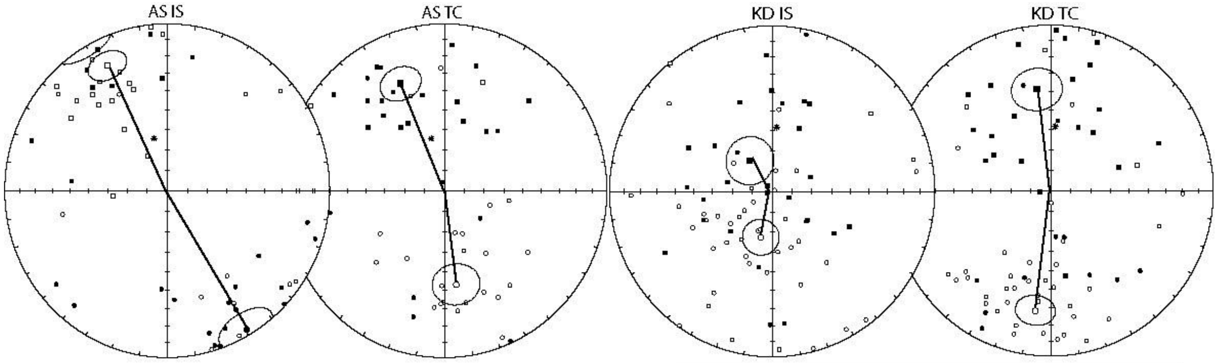
Reliability of the data

The primary nature of the ChRM directions was evaluated with the use of the reversal test of McFadden and McElhinny (1990) for the Aksu, Childara and Kuhdara sections. This was done independently for tilt corrected orientations. For the Shuldara section, the reversal tests were indeterminate because this section only showed reversed polarities.

The aim of this test is to compare the ChRM directions of the normal polarity zones with those of the reverse polarity zones. In an ideal situation, assuming no polar wander, no continental drift and perfect data, these directions are perfectly opposite to each other. These tests were done on the sections from this study and the results were quite disappointing. The tests were done for samples of the best quality showing distinct polarity and direction both for in situ and tilt corrected coordinates, for each section. For the Kuhdara and Childara sections the reversal tests failed. For the Aksu section the data passed the test with a C classification. This was for both the in situ and the tilt corrected coordinates.

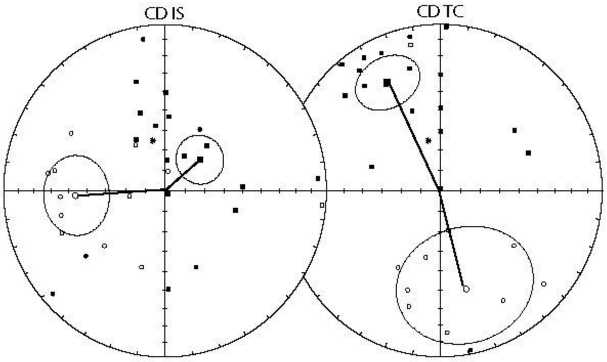
For the Childara section it was noticed in the field that the rocks had a slightly metamorphosed appearance, therefore an overprint could be the reason for these results. The samples from the Childara section also showed distinct overprints between 20˚C and 400-500˚C. The Aksu and Kuhdara sections did not show this, and at first sight especially the red muds from the Aksu section give decent paleomagnetic results. A lot of samples from the Aksu and Kuhdara sections do not show a decrease towards the origin. Furthermore is there a huge spread in directions for all sections. The Aksu and Kuhdara sections also seem to have experienced some remagnitization, especially the inversed polarity samples. For the Kuhdara sections the inverse polarity samples do not show the counterclockwise rotation anymore. (Fig. 7). The Kuhdara section has much more samples with an inverse polarity than normal polarity samples. This might also be the result of overprints. Except for the marine samples at the Kuhdara section there are not really intervals in the sections which show a significant decrease in sample quality. Magnetic intensities are much lower for sand samples than for mud samples in both the Aksu and Kuhdara sections, with sand samples having typical intensities of less than 1000×10^{2} mA/m. The terrain at the Kuhdara section showed some evidence of recent landslides or tectonics, which could also have moved the sampled sediments a bit, as they are mostly soft material from shallow river streams.

The calculated poles are plotted within a 95% confidence interval (a95). This a95 is calculated as a mean direction of the data point. As can be seen in figure 7, there is a lot of scatter in the data, therefore the a95 circles are large. Also the k values are low. The k values are an indicator of randomness, when the data is totally random, and the data points are evenly distributed over the plot area, the k value is 0, in our case the k values are all less than 10, which is very low.



IS	n	dec	inc	k	a95
N	27	333.5	-16.3	6.6	14.9
R	26	149.2	3.9	7.1	16.9
TC					
N	24	342.1	16.7	4.3	21.1
R	27	172.5	-43.1	7.0	17

IS	n	dec	inc	k	a95
N	18	314.8	65.6	6.0	21.0
R	39	177.5	-69.4	4.5	15.6
TC					
N	26	348.6	37.9	5.1	20.1
R	47	185	-29.0	4.4	14.3



IS	n	dec	inc	k	a95
N	14	50.4	66	4.4	21.6
R	14	268.3	-49.6	2.7	36.7
TC					
N	17	332.7	26.7	4.2	21.3
R	17	172.5	39.6	1.8	41.3

Figure 7 An overview of the Fisher mean directions shown in a stereographic plot for the Aksu (AS), Kuhdara (KD) and Childara (CD) sections both for in situ and tilt-corrected coordinates. Note the slight counterclockwise rotations on all sections, except the reversed intervals of the Kuhdara section.

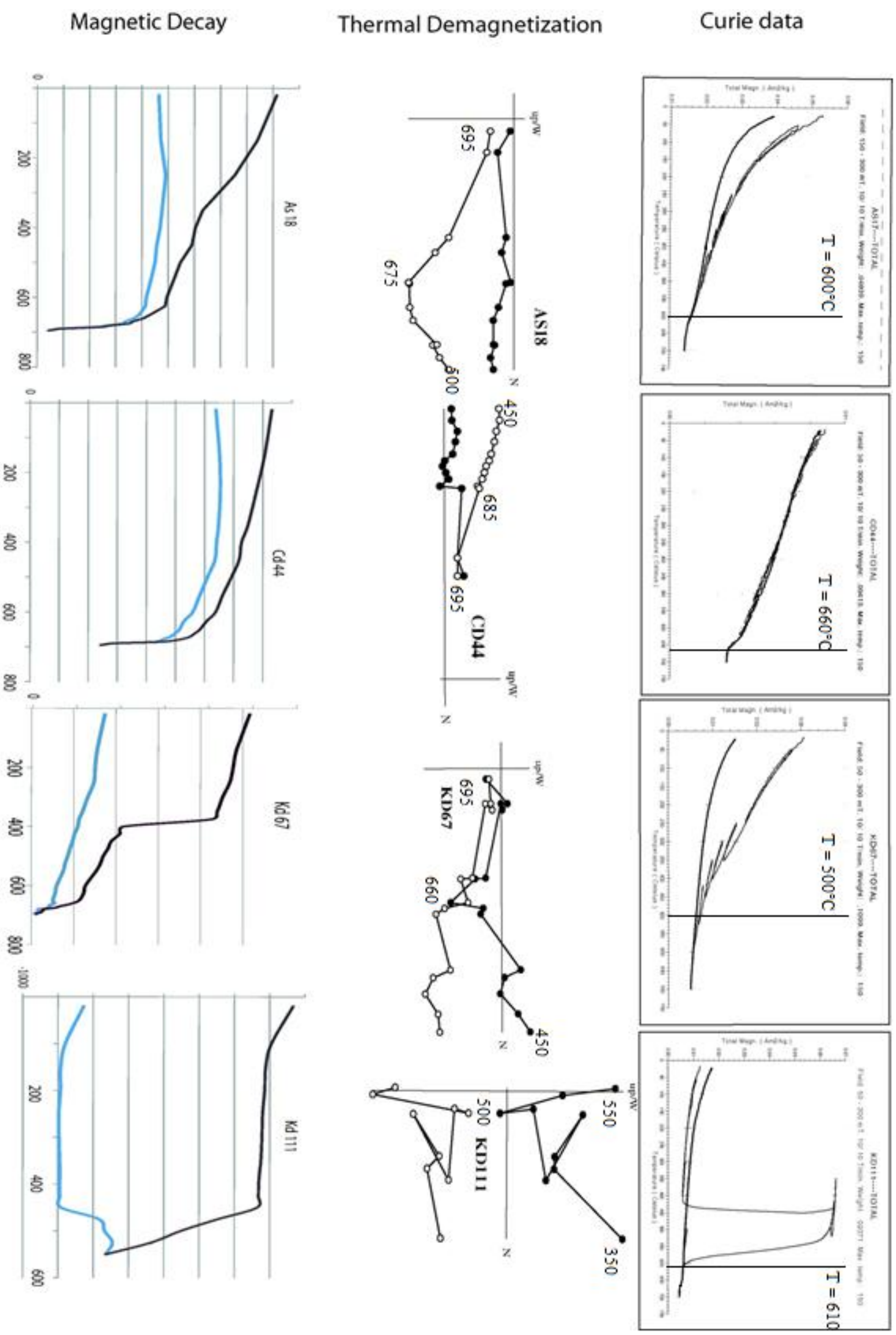


Figure 8 Rock magnetic results of four representative samples from different lithologies. AS17-18 are red muds, CD44 is a red fine sandstone, KD67 is a reddish-yellowish mud and KD111 a blue marine mud. The top row shows the Curie balance results, the second row shows the thermal demagnetization trajectories with temperature steps of 50°C until 500°C, 25° until 650°C and 5°C until 700°C. Temperatures shown are at the start, at the end and when directions change. The third row shows the decrease in magnetic intensity during thermal demagnetization.

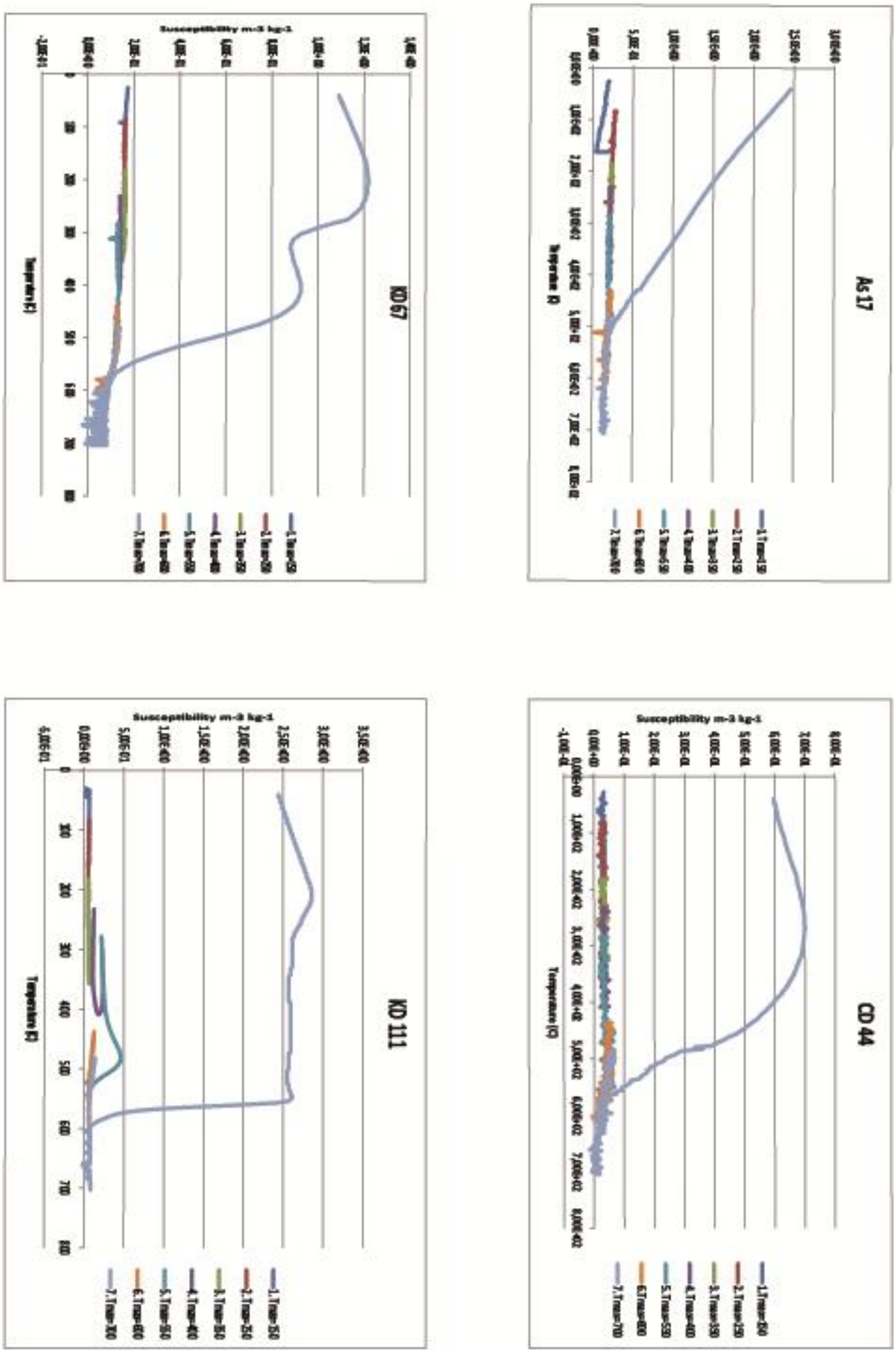


Figure 9 **KLY-3 Kappabridge results for four different samples. The different colors indicate the maximum temperature towards which the samples are heated. As can be seen most samples only show significant changes in susceptibility when they are heated to 700°C.**

GPTS correlation

After processing all data, a pattern of polarity zones could be recognized from the VGP latitudes of all four sections. The sections were correlated to the Geologic Time Scale 2012 (GTS2012) of Gradstein et al. (2012). Our correlations to the GTS2012 are constrained by our lithostratigraphic correlations to the second-last and last transgression of the southwest Tarim Basin, which have been constrained previously to the Lutetian and Priabonian respectively by integrated bio-magnetostratigraphic analyses (Bosboom et al., submitted). As the retreat of the sea was in westward direction, and the retreat is a process that happened over certain time it seems logical that the retreat from the Afghan-Tajik Basin took place after the sea had retreated from the Tarim Basin.

The Aksu section is divided in normal polarity zones N1, N2 and N3 from top to bottom (Fig. 3). The N1 chron is a relatively long normal polarity zone, followed by a short reversed interval and the short N2 normal interval. Below that is a longer reversed interval followed by the relatively short N3 normal interval. The Aksu section has been sampled directly after the marine-continental transition lithostratigraphically correlated to the final last sea retreat of early Priabonian age in the southwest Tarim Basin.

The first correlation that was made correlated the basal normal polarity (N3) zone of the sampled section is to C18n.1n as this correlation gives relatively little variation in sedimentation rate. This correlation implies that the top normal polarity interval N1 of the Aksu section will correlate to C17n.1n (Fig. 3). This however gives the sampled continental sediments a late Bartonian and early Priabonian age. The problem with correlation of the continental succession to chrons C18-C17 is that the underlying marine sediments which are correlated to the last marine regression of Priabonian age are definitely older than the sampled section. This would therefore imply that the retreat of the sea after the last transgression from the Afghan-Tajik Basin took place before the retreat of the last transgression from the Tarim Basin. As the Afghan-Tajik Basin is the only connection to the large Turan Sea in the west, and therefore the only connection to open water for the Tarim Basin, it is unlikely that the sea retreated from the Afghan-Tajik Basin before the westward retreat from the southwest Tarim Basin, as documented by Bosboom et al. (submitted). Other considered correlations for the Aksu section were to correlate the base normal polarity zone N3 to the C13n chron, N2 to C12n and N1 to C11n. This however gave a less reasonable fit with the normal and reversed polarity pattern as shown by the large variations in sedimentation rates, and was considered to be too young anyway to fit the established chronostratigraphic framework of the final sea retreat in the Tarim Basin, unless a sequence boundary associated to the sea retreat would separate the marine sediments from the overlying sampled continental succession. Also the correlation from base C9r to top at C9n was tested, but this gave a less good fit with the polarity pattern. Implying similar sedimentation rates as found in the southwestern Tarim Basin (5-25cm/kyr; Bosboom et al., submitted), correlation from N3 to chron C18n.1n and N1 to C17n.1n gives sedimentation rates of 15.3 cm/kyr for the bottom reversed interval, 2.9 cm/kyr for the N2 interval, 10.2 cm/kyr for the following reversed interval and 6.7 cm/kyr for the N1 interval. The sedimentation rate for the N2 correlation is low; the relatively large zones without a distinctive polarity on both side of the N2 interval could be the reason for this. So, after correlation with the GTS2012 of the paleomagnetic sampled interval of the Aksu section, there are still multiple options for the age of the last retreat.

The sampling of the Kuhdara section began at the end of its last marine-continental transition which is correlated to the second-last marine regression in the Tarim Basin (Bosboom et al., submitted), dated as ~41 Ma (near the base of C18r). The Kuhdara section is characterized by long reversed intervals, which makes correlation to the GTS2012 not straightforward. It was chosen to correlate the reversed intervals for this section instead of the normal polarities as the reverse polarities are much more abundant at the Kuhdara section. The reverse intervals were labeled R1-R4, with R1 at the top of the succession (see Fig. 4). R1 is followed by a short normal interval, followed by a relatively long reversed interval (R2). Below this is a relatively short normal interval followed by a short reversed interval (R3). This is followed by a relatively long interval with high uncertainties and a small normal polarity zone in the middle of it. After this comes the long reversed interval R4. The section ends with blue marine sediments which gave mostly unreliable data.

With expected sedimentation rates ranging between 5 and 25 cm/kyr and the ~41 Ma age estimate of the same marine-continental transition in the southwest Tarim Basin, a possible correlation of the basal reversed polarity zone (R4) would be with the C18r chron. This correlation gives a sedimentation rate of 20.1 cm/kyr. It was then chosen to correlate the R3 section to the C11r chron, R2 to C10r and R1 to C9r. This was chosen as it gave best fit with the sedimentation rates which are then 8.1 cm/kyr for the R3 interval, 12.5 cm/kyr for the R2 interval and 6.6 cm/kyr for the R1 interval. Sedimentation rates for the normal polarity zones between the R2 and R3 would then be 3.6 cm/kyr and between the R1 and R2 interval it would be 3.0 cm/kyr. This would imply however a major unconformity between the R4 and R3 interval. The large badly exposed zone between the stratigraphic levels 394.5m and 430.5m and the fact that the paleomagnetic results for this zone show a large uncertainty might be an indication that this is also the case. Therefore the correlation of the bottom reversed interval (R4) to the C12r zone is also a realistic possibility. This would place the unconformity in the large reversed R4 interval as the marine sediments below are definitely older. This option gives less reliable sedimentation rates and gave a less reasonable fit. Therefore the option to correlate the bottom part of the Kuhdara section to the first half of the Bartonian seems the preferred option. The top part is correlated to the Rupelian and early Chattian.

The Childara section is more difficult to correlate to the GTS2012 as it could not directly be linked to a continental-marine transgression (Fig. 5). The lithology of the section is very homogeneous and consists mostly of red fine sands from the stratigraphic correlations, suggesting that this section is at least younger than the second-last transgression, so younger than ~41 Ma. The section starts at the bottom with a long normal interval (N2), followed by a long reversed interval (R1) and ends with a normal interval (N1). Several options for correlation were considered, being to correlate the reversed interval R1 to the C17 chron, R1 to the C16r chron and the N1 interval to the C16n.1n chron, R1 to C15r and N1 to C15n and R1 to C10r and N1 to C10n. The correlation to C15 would gives a sedimentation rate of 16.8 cm/kyr for the R1 correlation and 13.0 cm/kyr for N1. The other considered correlations gave less reasonable sedimentation rates. The correlation to chron C15 would give the section a Priabonian age, implying the successions is younger than the final last transgression recognized in the Tarim Basin.

Because only a few samples were available from the Shuldara section and because they all show a reversed polarity it has been decided not to correlate this to the timescale. Because the sampled interval is positioned in between the deposits of the second-last and the last marine incursion in the Shuldara section (Fig. 6), the most likely option would be to correlate this reversed interval either to the C13r or C15r chrons, which would make this section of Bartonian age.

Rotations

To calculate the rotations in the Afghan-Tajik Basin, the Fisher mean directions of the sampled sections were compared to the Eurasian reference poles of Torsvik et al. (2008; see Table 1). This shows counterclockwise rotations as expected from Fig.ure 3. The rotations are around 30˚ for the Childara section, 20˚ for the Aksu section and 23˚ for the best quality samples of the Kuhdara section, but these decrease to 9˚ when the less quality samples are also considered. The problem is that the uncertainties are very high, up to 100% of the total rotation. This falls in line with the large spreading in results encountered earlier.

Table 1 **Rotation and flattening calculated from observed vs. expected directions.**

Section	Age	Group	Site location		Observed direction						Reference Pole				Rotation			Flattening		
			Latitude	Longitude	D_s	I_s	a_{95}	k	n	Reversals test	Age	Latitude	Longitude	a_{95}	R	±	ΔR	F	±	ΔF
	(Ma)		(°N)	(°E)	(°)	(°)	(°)			+/-	(Ma)	(°N)	(°E)	(°)	(°)		(°)	(°)		(°)
Childara	Bartonian-Rupelian	Quality 1	38.78	70.13	-24.4	31.9	33.6	3.5	21	-	30	82.7	152.5	2.8	-33.8	±	32.7	26.7	±	27.0
Childara	Bartonian-Rupelian	Quality 1+2	38.78	70.13	-18.3	33.9	34.3	2.8	33	-	30	82.7	152.5	2.8	-27.7	±	34.3	24.7	±	27.5
Aksu	Rupelian	Quality 1	38.12	68.58	-7.8	27.8	22.0	7.8	26	-	30	82.7	152.5	2.8	-17.1	±	20.2	30.1	±	17.7
Aksu	Rupelian	Quality 1+2	38.12	68.58	-15.2	36.5	16.2	5.7	35	-	30	82.7	152.5	2.8	-24.5	±	16.5	21.4	±	13.1
Kuhdara	Rupelian	Quality 1	38.64	68.89	-14.0	37.9	18.8	7.2	25	-	30	82.7	152.5	2.8	-23.4	±	19.5	20.5	±	15.2
Kuhdara	Rupelian	Quality 1+2	38.64	68.89	0.2	30.2	16.1	4.1	58	-	30	82.7	152.5	2.8	-9.2	±	15.2	28.2	±	13.0

Discussion

Timing of the sea retreat

The magnetostratigraphic results for the Aksu section give three possible options for correlation to the The first is to correlate the section to the C11n.1n to C9n chrons; this would give the sampled part of the section a late Rupelian to Chattian age. The second option would be to correlate the Aksu section to the C11n to C13n chrons, this would give an early to middle Rupelian age. The last considered option would be to correlate the Aksu section to chron C18n to C17n.1n. This would give the section a Bartonian to Priabonian age. The option to correlate the Aksu section to the C9-C11 chrons and the C11r-C12 chrons would involve the presence of an unconformity between the sampled section and the last marine sediments. The correlation to the C9-C11 chrons would give the section an age of ~26-~30 Ma, and the correlation to the chrons C11n-C13n would give ages between ~30 Ma and ~34 Ma. The correlation to the C9-C10 chrons would be the slightly favorite with respect to the sedimentation rates compared to the C11-C13 correlation.

As the last sea retreat is probably older than the Eocene-Oligocene transition (EOT) (Bosboom et al., submitted), there must be a major unconformity between the last marine sediments of the last marine interval and the sediments of the section sampled at the Aksu. This unconformity has not been observed in the field due to the poor exposure, but would be feasible in relation to the data. This hiatus, that is of around the same age as the EOT is also described by Bosboom et al. (submitted) in the Tarim Basin and is most likely related to the major ~70 m sea level drop documented at the EOT around 34 Ma (Katz et al., 2008; Lear et al., 2008; Miller et al., 2005; Pekar et al., 2002). The preferred correlation for the Aksu section would therefore be to the C9-C11 chrons. During this time sedimentation could start due to uplift processes of the Pamirs. The unconformity would then have covered at least the C12 and C13 chrons.

The R1, R2 and R3 reversed polarity intervals of the Kuhdara section give a relatively good fit to the C11r-C9r chrons. This would make this part of the section of Rupelian to Chattian age. This is similar to the correlation established for the upper continental part of the Aksu section. The marine sediments at the base are interpreted as being deposited during the second-last marine interval, dated as Lutetian in the southwest Tarim Basin (Bosboom et al., submitted). A part of this marine sequence was also sampled for paleomagnetic investigation, and although the marine sediments did not give reliable results, there was some alternation between marine and continental sediments before there was a definitive shift to continental deposition. This short regressive interval of reversed polarity should therefore likely correlate to the C18r chron. This correlation would have as a consequence that the second-last regression takes place in the Afghan-Tajik Basin more or less at the same time as in the Tarim Basin. These observations also strengthen the theory of the unconformity in the Aksu section between the deposition of the last marine sediments and the continental deposits. Another option would be to correlate the reversed interval R4 to the C12r chron. This would place the unconformity in the large reversed polarity interval R4, as the underlying marine sediments are most likely older. If the bottom reversed interval of the Kuhdara section is correlated to the C12r chron, this would mean we have an unconformity around the same time at this section as at the Aksu section after which sedimentation started again around 31 Ma, probably caused by the start of the uplift of the Pamir mountain range. This unconformity is most likely related to the large ~70 m global sea level fall at the EOT, which probably had a large effect on the shallow epicontinental basins. Therefore this could be the reason why there is no last last transgression recorded at the Kuhdara section, as the incision related to the base-level drop may eroded the underlying sediments. Another option for not finding the last transgression and regression at the Kuhdara section could be the fact that it has never been deposited.

The Childara sections is correlated to the C15 and C16 chrons, which would give it an age between the last and second-last marine intervals. The Shuldara section is correlated to the C15 interval which makes it around the same age as the Childara section.

Paleogeography

The Afghan-Tajik Basin formed part of the Turan Sea, and was connected to the Tarim Basin in the east at least until the early Bartonian (Bosboom et al., submitted). The Turan Sea was a large shallow sea that stretched from the Tarim Basin in western China to the present-day Caucasus and succeeded into the Atlantic Ocean, which covered most of present day Europe during the Priabonian. The sea was connected to the Arctic Ocean via the Turgaj Strait and the Western Siberia Basin (Popov et al., 2004). The Turan Sea was part of the vast amount of basins that separated the Eurasian, African, Arabic an Indian plates before they collided during the Eocene and formed the Alpine-Himalayan realm. After the collision of these continents the vast amount of water of which the Turan Sea was a part became the Paratethys, an inland sea which was only connected to other Oceans in the west with the Atlantic Ocean. (Popov et al., 2004)

During the Eocene, the sea started moving westwards from the Tarim and the Afghan-Tajik Basin. The last westward retreat from the Tarim basin was during the Priabonian. (Bosboom et al., submitted). Due to the diachroneity of the westward retreat it is expected that the sea retreat from the Afghan-Tajik Basin occurs at a later stage. Because the Central Asian basins were relatively shallow, with depths of less than 200 m (Bosboom et al., submitted), relatively small variations in sea level have large effects on the presence of the sea and the connectivity between the basins. Therefore it is expected that there is not a large difference in timing between the retreat of the sea from the Tarim Basin and the Afghan-Tajik Basin.

Most of the fluvial sediments that have been sampled for this research are interpreted as being of an early Oligocene age. This means that after the EOT there were continental conditions in the Afghan-Tajik Basin. The EOT is dated at ~34 Ma, and is characterized by a shift from a greenhouse to an icehouse earth (Miller et al., 2005) that led to a major global sea-level drop of ~70 m (Katz et al., 2008; Lear et al., 2008; Miller et al., 2005; Pekar et al., 2002). This major sea-level drop would have had a massive impact on the shallow, epicontinental seas in Central Asia. It seems therefore reasonably to assume that during the EOT there was no sedimentation, and even erosion in the basin.

This lack of sedimentation during the EOT would be a likely explanation for the possibly encountered unconformity between the last marine sediments and the continental sediments that were deposited after the EOT.

Our findings on the presence of the Turan Sea at the Afghan-Tajik Basin are in agreement with the findings by Popov (2004, 2010) who shows that the sea shifted westwards during the late Eocene and established an eastern boundary at the Elburz-Kopetdagh High during the early Oligocene. As shown by Popov (2004), during late Eocene the Afghan-Tajik Basin together with the Fergana Basin in present day Kyrgystan forms an eastern sea inland from the Turan sea which is bounded to the north by the Tien Shan and in the south by the North Pamir land. In the east is the Tarim Basin from which the eastern margin of the sea is moving in a westward direction.

From previous work by Bosboom et al. (Submitted) we know that during the late Eocene the sea had its eastern margin in the Tarim Basin in western China. As shown in the map by Popov (Fig. 10), during the early Oligocene, the sea had an eastward margin around present day Uzbekistan and Turkmenistan. This means that the final regression caused a westward movement of the eastern margin of the sea of over 500 km in a time span of only a few million years.

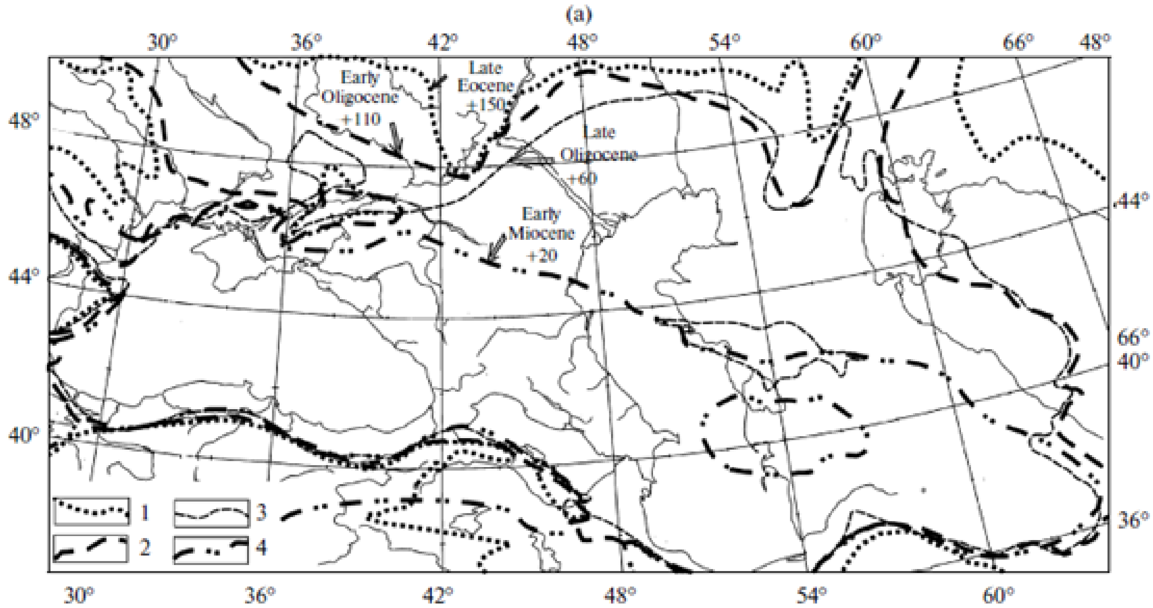


Figure 10 **Map of the proto-Paratethys realm and shorelines of transgression phases by Popov (2010). (1) Late Eocene, (2) Early Oligocene, (3) Late Oligocene, (4) Early Miocene. The Afghan-Tajik basin is situated out of the eastern margin of this map.**

Cause and implications of the retreat

The two most likely mechanisms that have controlled the retreat of the sea from the Afghan-Tajik basin are regional tectonic processes, for instance the uplift of the Pamir mountains caused by the India-Eurasia collision and larger scale sea-level fluctuations, or a combination of both.

As the last regression from the Afghan-Tajik Basin most likely took place during the Priabonian, after the retreat from the Tarim Basin during the early Priabonian (Bosboom et al., submitted) and the EOT, there are multiple processes that could have played a role in this final retreat.

As the retreat most likely took place during the Priabonian, after the sea retreat from the Tarim Basin, a process that is likely to have had influence on the sea retreat is the short-term global cooling effect that is reported in the early Priabonian by a positive peak in $\delta^{18}O$ in the Southern Ocean (Villa et al., 2008), and by an elevated $CaCO_3$ interval in the equatorial Pacific (Lyle et al., 2005). The global sea-level curves from Miller et al. (2005) show a drastic decrease in sea-level in the late Eocene, starting around the C16 (~36 Ma) chron, which could be an indication that global sea-level fluctuations played an important part in the retreat.

The other possible cause for the retreat of the sea from the Afghan-Tajik Basin could be related to early uplift of the Pamir mountain ranges in the east. The possible absence of the last transgression at the Kuhdara section might be an indication of early uplift, and the fluvial sediments found after the last regression both at the Aksu and the Kuhdara section could be equivalent to the continental red-beds found by Sun et al. (2013) in the southwestern Tarim Basin who interprets these as molasse sediments which relate to an early Pamir uplift event at 34 Ma. Most other sources however state that the uplift of the Pamir did not start until the Neogene. (Bershaw et al., 2012; Sobel et al., 2012; Brookfield et al., 2001). As the first recorded collision between the Indian plate and the Eurasian plate is however dated at ~50 Ma (Van Hinsbergeb et al, 2012), there is a possibility that tectonics started to have some effects on the topography of the region since the initial collision.

The studies of Ramstein et al. (1997) and Zhang et al. (2007) suggest that the Central Asian epicontinental basins were the main source of moisture for the Asian interior, and that the retreat of the sea from Central Asia would have most likely caused an increased aridity in the Asian interior by enhancing the land-sea thermal contrast. As the retreat of the sea from the Afghan-Tajik Basin has not been exactly dated in this study, it is not possible to exactly correlate events to the sea retreat in the Afghan-Tajik Basin, but by using the interval in which the sea retreated and guided by the sea retreat from the Tarim Basin, there are several recorded possible consequences on the Asian climate caused by the sea retreat.

Research from Dupont-Nivet et al. (2007, 2008) and Xiao et al. (2010) using precisely dated pollen and sedimentologic records indicate regional aridification in the Xining Basin along the northeastern Tibetan Plateau at the 34.0-33.8 Ma EOT. This aridification step could be driven by the retreat of the sea from the Central Asian basins, but more likely it is an effect of global climatological changes at the EOT. Abels et al. (2007) recorded another aridification step around 37.6 Ma (top chron C17n.1n) which is very close to the retreat of the sea from the Tarim Basin (Bosboom et al., submitted) and therefore most likely also to the retreat from the Afghan-Tajik Basin. This correlation would suggest that the Afghan-Tajik basin along with the other Central Asian basins behaved as a major contributor of moisture for the Asian interior during the Paleogene. This is supported by the large western movement of over 500 km as shown by the Figure of Popov (2010) (Fig. 9). This huge sea retreat from the center of the Asian continent makes it very likely that this would have had a serious impact on the moisture supply of the Asian continent.

Rotations

To investigate the role of the uplift of the Pamir mountains on the deformation history of the Afghan-Tajik Basin a small investigation of the rotation history of the Aksu, Kuhdara and Childara section was done by comparing the Fisher mean directions with the Eurasian reference poles of Torsvik et al. (2008; see Table 1) All sections show a counterclockwise rotation between roughly 10° and 30°. There is however a large uncertainty in these calculated rotations, but they seem comparable to the rotations measured by Thomas et al. (1994) and Pozzi and Feinberg (1991) in the Afghan-Tajik Basin, which give average rotations in the Afghan-Tajik Basin of -39.3°. The results fit with the theory of rotational northwest-directed radial thrusting on the western side of the Pamir (Cowgill, 2010. Fig. 10, A). Cowgill (2010) shows that based on the insignificant vertical-axis rotation results by Rumelhart et al. (1999), transfer faulting took place on the eastern side of the Pamir, resulting in the asymmetric geometry of the Pamir.

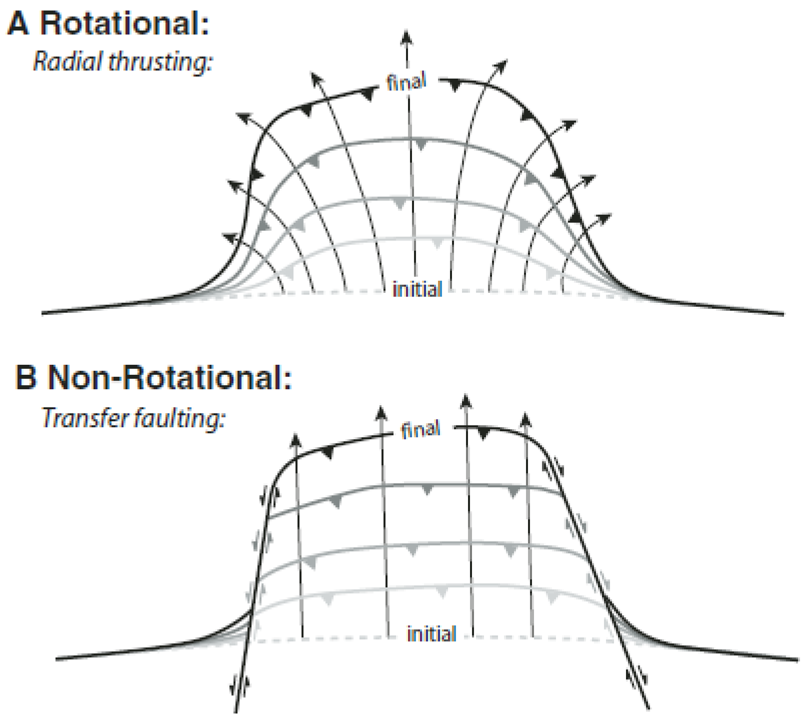


Figure 11 **A schematic image of different models for the formation of the Pamir Mountain range by Cowgill (2010). Based on the rotation results from this study, the radial thrusting rotational model seems to be the most likely.**

Conclusions

The most important conclusion from this study is that the last retreat of the sea from the Afghan-Tajik Basin took place between ~37 Ma and ~34 Ma, between the last regression from the Tarim Basin and the EOT. Because the sampled sections are mostly continental deposits, and therefore deposited after the last regression, it is not possible to give an exact age for the deposits of the marine intervals in the Afghan Tajik Basin. However, due to the westward movement of the sea and the and the more exact dated retreat from the Tarim Basin in the east, we can give an age range of the retreat.

Another major finding is that the unconformity found in the Tarim basin at the EOT is most likely also present in the Afghan Tajik basin, which would suggest a connection between both basins at least until the EOT. Sedimentation seems to start again at ~31 Ma, which is most likely related to Pamir uplift.

Both the second-last and the last marine incursion recorded in the Tarim Basin are found in the Afghan-Tajik Basin, this implies that the processes controlling the transgressions and regressions and the final retreat of the sea from both basins has the same origin. The cause of the retreat is therefore most likely related to larger scale climatological and eustatic processes, as indicated by global cooling studies and sea-level curves of the Eocene. It is however very likely that early uplift processes of the Pamir mountain range caused by the Eurasia India collision and subsequent sedimentary infill also had an influence in the shift from marine to continental conditions. A rotation study was done to look at the influence of the Pamir mountain range uplift at the sampled sections and this shows counterclockwise rotations between 10° and 30°. It is shown that this rotation relates to northwest directed radial thrusting on the western side of the Pamir, which is probably of Neogene age.

After the final transgression there was a westward regression of over 500 km. This very large retreat of the sea from the center of the Asian continent is likely to have had a big impact on the moisture supply of the Asian continent.

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