Glacio-Marine Transgressions of the Early and Middle Pleistocene Caspian Basin, Azerbaijan

Christiaan G.C. van Baak

August 23, 2010

Paleomagnetic Laboratory "Fort Hoofddijk", Utrecht University, Budapestlaan 17, 3584 CD Utrecht, The Netherlands

Abstract

Establishing an unambiguous timescale for the Late Neogene deposits of the Eastern Paratethys region has been a problem for years due to contradicting paleomagnetic results and local biostratigraphic schemes. This work aims to create a reliable magnetostratigraphy for key sections in Azerbaijan. The boundary between the Productive Series and Akchagylian regional stages, as observed in the Lokbatan section, has in the most likely scenario an age of 2.5 Ma, as opposed to 3.4 Ma in most existing correlations. The younger regional stages, the Apsheronian and the Bakunian, yield ages for their lower boundary of older than 1.8 Ma, and 0.88 Ma. In this new chronostratigraphic framework, transgressions at the base of both the Akchagylian and the Bakunian fall within cold intervals of the Pleistocene (marine isotope stages 100-96 and 22 respectively), and are thus likely to have an origin related to Northern Hemisphere glaciation. Existing hypotheses explain Late Pleistocene ice-dammed lakes and reversed river drainage stretching from Scandinavia to West Siberia as a possible cause for transgressions. A similar hypothesis is proposed for the Akchagylian transgression. Species with an Arctic origin found in the Caspian Sea prove this connection with the Arctic ocean. Of these species the Caspian seal is an interesting example, especially since it is hypothesized to have entered the Caspian Sea around 2-3 Ma.

1 Introduction

1.1 Caspian and Paratethys sea-level changes

In the past 7 Myr the Caspian Basin has been characterized by large lake-level variations with differing amplitudes (Popov et al., 2010). After the restriction during the deposition of the Mio-Pliocene Productive Series (PS), a number of important transgressions took place in the Plio-Pleistocene (Abreu and Nummedal, 2007). The earliest of these large transgressions of the Caspian Sea is the Pliocene Akchagylian transgression, which marks the end of the Productive Series and the beginning of the Pliocene Akchagylian deposition in the Caspian Sea. This transgression has at present an age of 3.4 Ma (Jones and Simmons, 1996). The origin of the Akchagylian transgression has been linked to a eustatic highstand, that caused overflow of marine waters into the Caspian Sea. The exact location of this connection to the ocean remains unclear (Popov et al., 2006). The interpretation of this transgression is mainly based on biostratigraphic zonations (Nevesskaya et al., 2002) and, unfortunately, no direct absolute chronostratigraphic correlation to the global record exists. The idea of a marine origin of the Akchagylian transgression lies in the Paratethys origin of the Caspian Sea, which had, at times, connections with the open ocean, followed by periods of more restricted conditions (Krijgsman et al., 2010). In the Akchagylian a subdivision in three stages can be made, either based on transgressive/regressive cycles or on the basis of fossil assemblages (Jones and Simmons, 1996, Nevesskaya et al., 2002).

Younger (Pleistocene) transgressions have been interpreted in terms of overflow of pro-glacial lakes during extensive glaciations when land-ice blocked the north-flowing rivers from Scandinavia to Siberia (Arkhipov et al., 1995, Grosswald, 1998, Mangerud et al., 2001). A detailed age for these transgressions allows for discriminating between a glacial and marine origin. Detailed timing however, is scarce for the Eastern Paratethys region for the past 4 Myr, where stage boundaries are solely based on biostratigraphic events. Existing magnetostratigraphic correlations disagree with each other and are restricted to publications in other languages than English. The scope of this paper is to create a timescale based on long sections in time and use this timescale to date precisely the times when the depositional system switched from marine to proglacial transgressions.

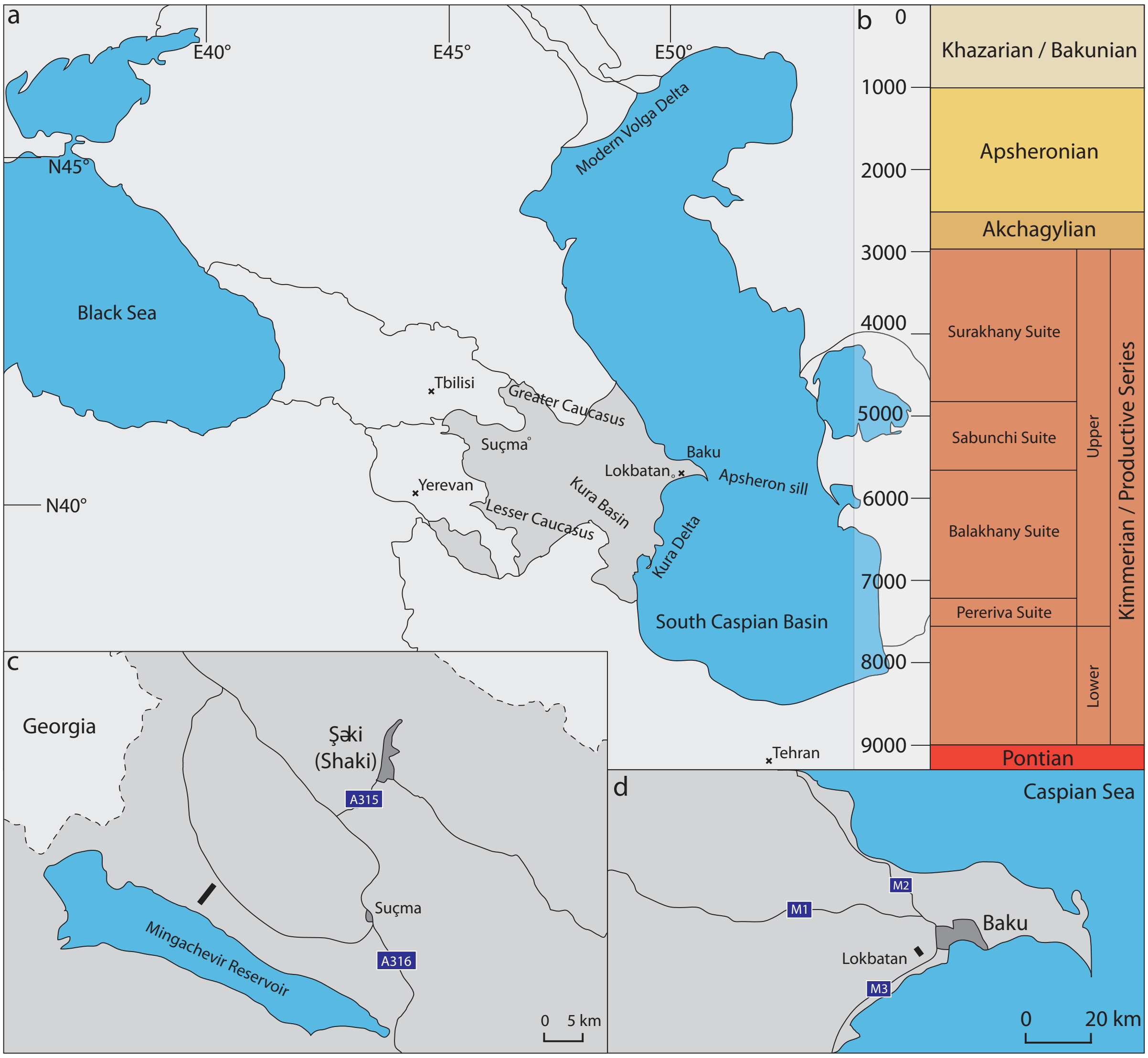

Figure 1: Schematic map and overview of regional stages; a) map of the greater Caspian- and Black Sea area; b) Caspian regional stages, left column; stratigraphic thickness in the South Caspian Basin (from Allen et al. (2002), Hinds et al. (2004)); c) detailed location map of the Suçma section; d) detailed location map of the Lokbatan section. Thick black lines in c and d represent section locations.

1.2 Existing timescales

The most cited timescale for the Caspian Sea is by Jones and Simmons (1996), who provided a complete review of available data and incorporated the regional stratigraphic stages in a global framework using biostratigraphic and magnetostratigraphic correlations, calibrated against global sea-level curves (figure 1b for the stratigraphic thicknesses, figure 2 for the array of existing ages).

For instance, they show that the Kimmerian regional stage (Productive Series of the Caspian Sea) can be calibrated against Chron C3A and the Gilbert Chron. On the basis of this magnetostratigraphic evidence, including an old correlation of the underlying Pontian, they propose a correlation between the major unconformity at the base of the Kimmerian against the 5.5 Ma eustatic sea-level lowstand. In the overlying Akchagylian regional stage (calibrated against (part of) Gilbert, or Gauss to Matuyama chrons), the three major transgressions are then related to 3.4 Ma, 2.7 Ma and 2.0 Ma global maximum flooding surfaces. The restricted nature of the Caspian Sea in the Kimmerian makes this correlation with global standards unlikely since from the Mio-Pliocene onwards a dominant control of the Volga-river is suggested for lake-level variations (Dumont, 1998). Furthermore, recent work in the Dacian Basin in Romania dates the Pontian younger from 5.9 Ma to 4.9 Ma (Vasiliev et al., 2004). This shows the complexity of correlating the existing biostratigraphic zonations of the Eastern Paratethys between the Dacian, Black Sea and Caspian Basins and the need for accurate magnetostratigraphic dating in each

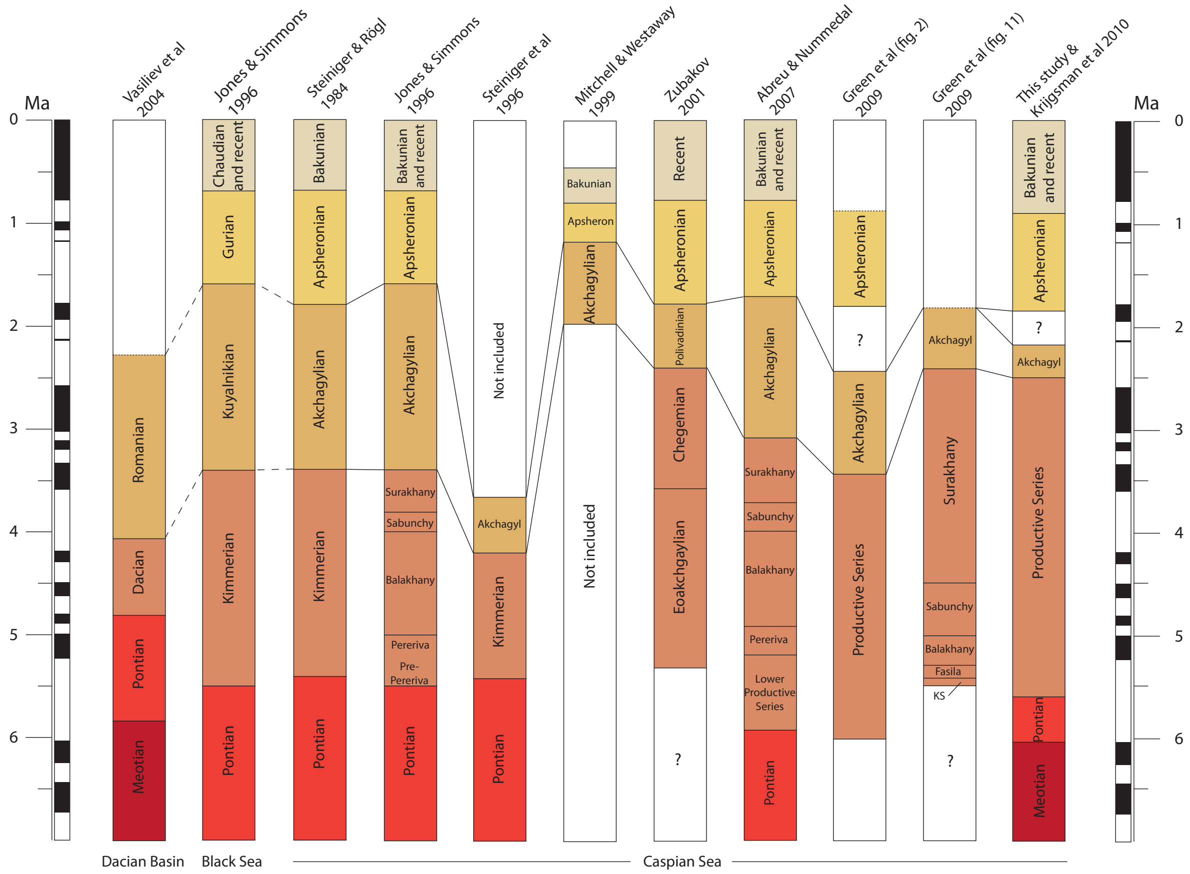

Figure 2: Existing Caspian Basin and Eastern Paratethys timescales. Lines connect the upper and lower boundaries of the Akchagylian regional stage.

basin.

The Pleistocene regional stages (Apsheronian and Bakunian) are dated more accurately and yield a base Bakunian-age just older than the Matuyama-Brunhes reversal (0.8 Ma) and base Apsheronian around the Olduvai subchron (1.6-2.0 Ma) (Jones and Simmons, 1996, Zubakov, 2001).

In the lowermost part of the Akchagylian a series of thin tuff intercalations (5-15 cm thick) is found. Two radiometric dates are quoted for this ash-layer, although the original work is not publicly available. The article by Devlin et al. (1999) quotes an age of 3.4 Ma for ash beds in the lower part of the Akchagylian based on work by Chumakov et al. (1988), which however does not contain these dates, only fission track dates of Pontian and older ash layers in Azerbaijan. A second (potential) reference to this ash layers comes from articles by Abdullayev (2000) and Fowler et al. (2000). Both articles claim an age of 2.4-2.6 Ma for ash beds in the lowermost Akchagylian, but cite different conference abstracts (Groves et al., 1996, Smale et al., 1997). Mitchell and Westaway (1999) indicate that Soviet studies place the Akchagylian transgression around 2.5 Ma or around 1.8 Ma. They then place it themselves at 1.2 Ma. They propose a correlation of a base Apsheronian normal period with the Cobb Mt. cryptochron (1.22 Ma) which would lower the base of the Akchagylian to 2 Ma.

Knowing the exact age of the Akchagylian regional stage by means of magnetostratigraphy is thus the key first step to be made in establishing the Plio-Pleistocene correlation of the Paratethys region with the global Neogene timescale and in answering the question on the origin of this major transgression.

2 Geological setting and sections

2.1 Geological setting

The Productive Series of Azerbaijan is the main reservoir unit of the South Caspian Basin oil-province. It consists in the basin center of up to 7 kilometers of Late Miocene to Pliocene fluvial and deltaic deposits. These deposits are subdivided in nine suites, boundaries are defined at regional flooding surfaces and sequence boundaries (Reynolds et al., 1998). The start of PS deposition is correlated with the Messinian salinity crisis (MSC), the coincident base-level drop caused the concentration of deposition in the small South Caspian Basin (Jones and Simmons, 1996). At roughly the same time uplift of the Caucasus caused a further decrease of connectivity with the Black Sea. Sedimentation rates remained high in the South Caspian Basin over the past 5.5 Myr, with an average of around 2 m/kyr (Knapp et al., 2004). These high sedimentation rates are interpreted to be related to increased tectonic subsidence due to sediment loading and compaction on a thermally subsiding oceanic or thinned continental crust (Zonenshain and Le Pichon, 1986). In addition the South Caspian basement is being subducted towards the north beneath the central Caspian region (Egan et al., 2009). Recent models also predict that the Productive Series may have been deposited in a topographic depression as deep as 1.5 km (Green et al., 2009). In this depression three major rivers (Volga, Kura and Amu Darya) deposited their enormous sedimentary load eroded from the newly formed mountain ranges like the Caucasus and the Kopet-Dagh (Brunet et al., 2003).

The relative importance of these three river systems varied trough time (Abreu and Nummedal, 2007), with the Volga delta being the most important during the deposition of the lower and middle part of the Productive Series, while for the uppermost Productive Series (Surakhany suite) the Amu Darya became the most important sediment source. This is also the moment the Caspian Sea started expanding north and deposition became more mud-dominated (Hinds et al., 2004).

2.2 Paleomagnetic setup / sections

2.2.1 Lokbatan

The Lokbatan section (N 40°20'43", E 49°44'35"), located 12 km west of Baku, covers (part of) the Surakhany suite of the Productive Series, the Akchagylian and at the top of the valley the Apsheronian starts. The total stratigraphic thickness of the sampled section is 470 meters, in which 205 levels are sampled, 92 in the PS, the rest in the Akchagylian. The section is very well exposed and the freshest parts outcrop along a series of small gulleys in the main valley. Laterally the outcrop is very continuous, allowing for stratigraphic jumps to adjacent gulleys. The lower part of our section is the uppermost part as described by Hinds et al. (2004), who interpret deposition to have taken place in both terrestrial and subacqueous environments on a muddy plain.

The 260 meters of PS deposits are characterized by an alternating package of predominantly gray silty clays and (sub-) meter-scale friable sandstone layers. The boundary with the Akchagylian is placed at the last sandstone layer, after which the section is characterized by 200 meters of occasionally fossil-rich (Dreissena rostriformis, Didacna sp.), fine layered dark clays and silts. At 90 meters into the Akchagylian a 10 meter thick layer of fine-bedded blackish clays is found in which no ostracods and mollusks have been recognized, interpreted as an anoxic event (see figure 3). The bedding dip of the layers varies from 55° to 40° for the lower part of the section, at 150 meters into the Akchagylian a sudden change to a dip of 25° is observed. Whether this represents a true unconformity is unknown at present, but can be constrained by dating the ash-layers found in the section above and below it (figure 3). The top of the section is marked by two beds of slumped layers in which reworked tuff elements and shell-fragments are found. The top of the section is stratigraphically roughly halfway into the Akchagylian.

2.2.2 Suçma

The Suçma section lies in western Azerbaijan (N 40°59'50", E 46°48'52"), 38 km southwest of Shaki, on the northern flank of an E-W-trending anticline north of the Mingachevir Reservoir, where deposits of Akchagylian, Apsheronian and Bakunian age are exposed. The anticline forms part of the Kura fold-thrust belt, which is the actively deforming southern margin of the Greater Caucasus and is thought to have accommodated 30-40% of the shortening between Arabia and Eurasia in the past 5 million years (Forte et al., 2010). Not much is known about thickness of the different formations in this part of Azerbaijan (see Forte et al. (2010) for an overview), but most likely decreases from east to west and across structures.

In the 900 m long section a total of 97 levels were sampled, using oriented hand samples and standard paleomagnetic cores. The base of the section lies within the Apsheronian, the Akchagylian is not exposed on this flank of the structure, but fossil-rich mudstones distinctly different from the overlying Apsheronian are reported from the southern flank (A.M. Forte pers. comm., 2010). The extent of the Akchagylian and exact location of the Apsheronian boundary can only be based on existing geological maps at the moment and is thus possibly not precisely known.

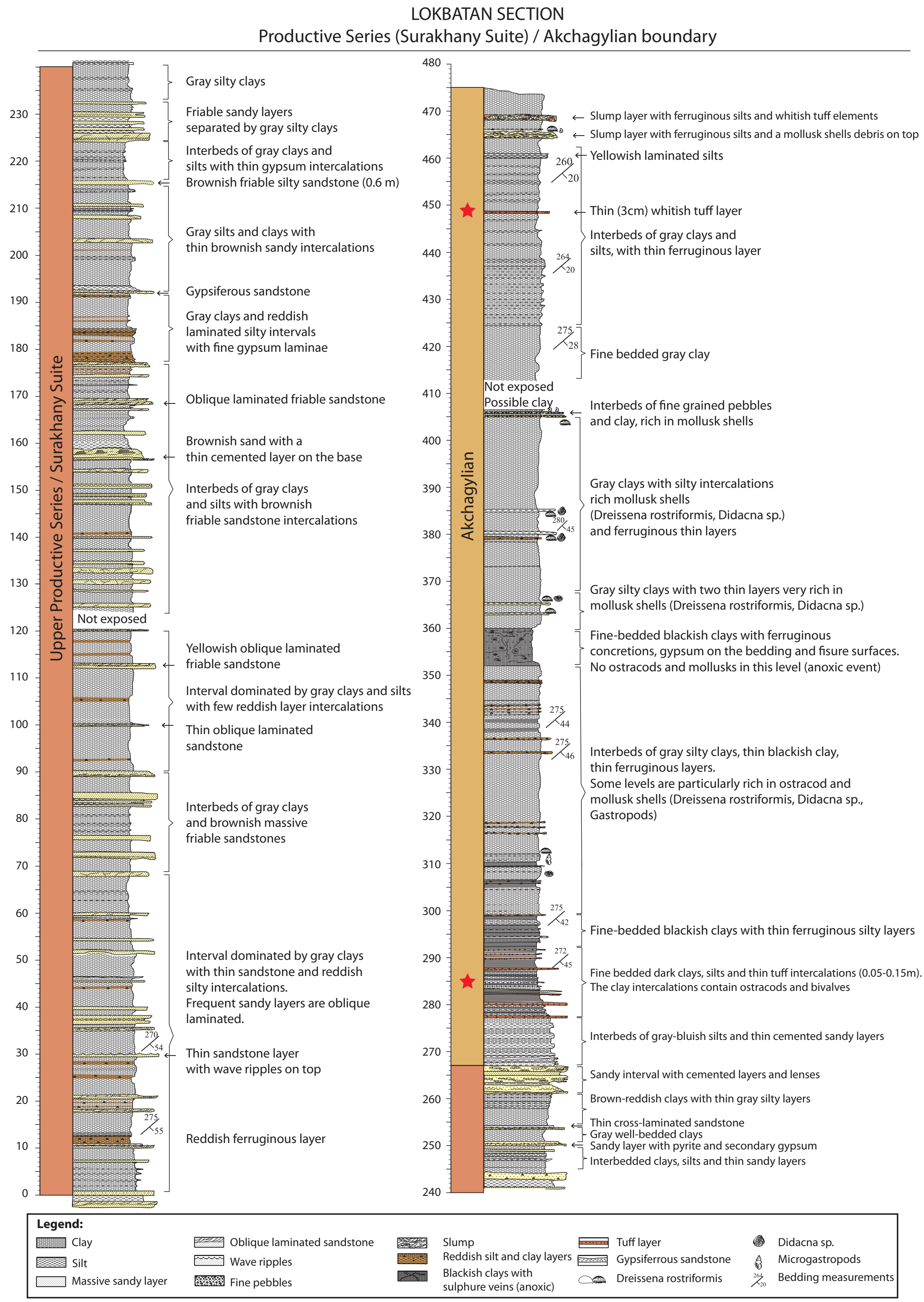

Figure 3: Detailed sedimentary log of the Lokbatan section. Red stars represent the position of ash-layers in the section (also in further figures).

The section consists of gray and brown silts, with a section-upward increase of 1-5 meter thick sandstone and conglomeratic layers. At level 460 m a meter-thick ash-layer was found and sampled for radiometric dating. The base of a 20 m thick finely laminated dark mudstone marks a short transgression and the end of the Apsheronian. In the overlying Bakunian, a package of fine and coarse sandstones is found. In the uppermost part of the section the sediments become more silty again and also unconsolidated, making them unsuitable for paleomagnetic sampling. The bedding dip changes in this higher part from a relatively steep 55-70° (as found in the lower part) gradually to less then 35°.

A second, shorter section was sampled 5 km northwest along-strike (N 41°0'59", E 46°45'25"). Forty stratigraphic levels over 120 meters were sampled, including two, meter-scale ash-layers, at the top and base of the section. One of these is the equivalent of the ash-layer found in the main section, but from field observations this could not be deduced.

Both the Lokbatan and Suçma paleomagnetic samples were taken with an electrical drill and a generator as power supply, taking two standard-oriented cores per stratigraphic level. The entire Suçma section was originally sampled using oriented handsamples, which were in the lab put in gypsum for support and drilled using compressed air, but where drilled cores and handsamples were available (29 of the 97 sample sites), drilled cores were analyzed. Additional samples were collected for biostratigraphic and geochemical purposes. Sandier layers were mostly not sampled since these are more prone to record a present-day-field (pdf) overprint in these type of sedimentary settings and thus provide lower quality demagnetization results.

3 Results

3.1 Methods

The magnetostratigraphy for the Lokbatan and Suçma sections is based on thermal demagnetization (TH) of at least one sample per stratigraphic level. Demagnetization was performed with temperature increments of 10-50°C, up to a maximum of 600°C, in a magnetically shielded, laboratory-built, furnace. The natural remanent magnetization (NRM) was measured on a horizontal 2G Enterprises DC SQUID cryogenic magnetometer (noise level $3\text{x}10^{-12}$ Am^2). Results were plotted in Zijderveld diagrams (Zijderveld, 1967), in which the directions of the NRM components were calculated by principal component analysis (Kirschvink, 1980). Additionally, when thermal demagnetization was not conclusive, a second sample was demagnetized using alternating fields (AF) with small increments up to a maximum of 100 mT after first being heated to a temperature of 150°C, removing most of the overprint (Van Velzen and Zijderveld, 1995). Samples were measured on an in-house built robotized sample handler controller attached to a horizontal 2G Enterprises DC SQUID cryogenic magnetometer.

3.2 Thermal and alternating field demagnetization

3.2.1 Lokbatan

During the thermal demagnetization of Lokbatan samples a low-temperature, secondary, overprint was removed in most samples up to a maximum temperature of 300°C or fields of 10-15 mT. The high-temperature (HT) or high-coercivity (HC) component was, where present, identified above this temperatures. Figure 4 shows orthogonal vector diagrams with tectonic correction (tc) and without tectonic correction (notc). Thermal demagnetisation diagrams show different types of magnetic behaviour that have a clear relationship with lithology. Based on the maximum demagnetisation temperature the samples could be divided into two major groups. The first group represents the demagnetization of iron oxides, the second represents iron sulphides.

Iron oxides The iron oxide group of samples is found as the dominant type of magnetization for the PS and part of the Akchagylian samples. Figure 4 a,b,d,e show typical behaviour for these samples, where 4a,d have high intensities (10's of mAm^{-1}) typical for the PS and 4b,e low, typical for the Akchagylian samples. The majority of the Akchagylian samples tend to have an intensity three orders of magnitude lower than the PS samples. Upon demagnetization no significant increase in susceptibility is found. For temperatures up to 250-300°C a secondary, and likely present-day overprint can be isolated in most of the samples. Some samples show a minor overprint to temperatures of 100°C. After the removal of this first component, a linear decay of the NRM is found up to temperatures of 540 - 600°C. AF-demagnetization was performed on all lower intensity Akchagylian samples and isolates a component at fields above 30

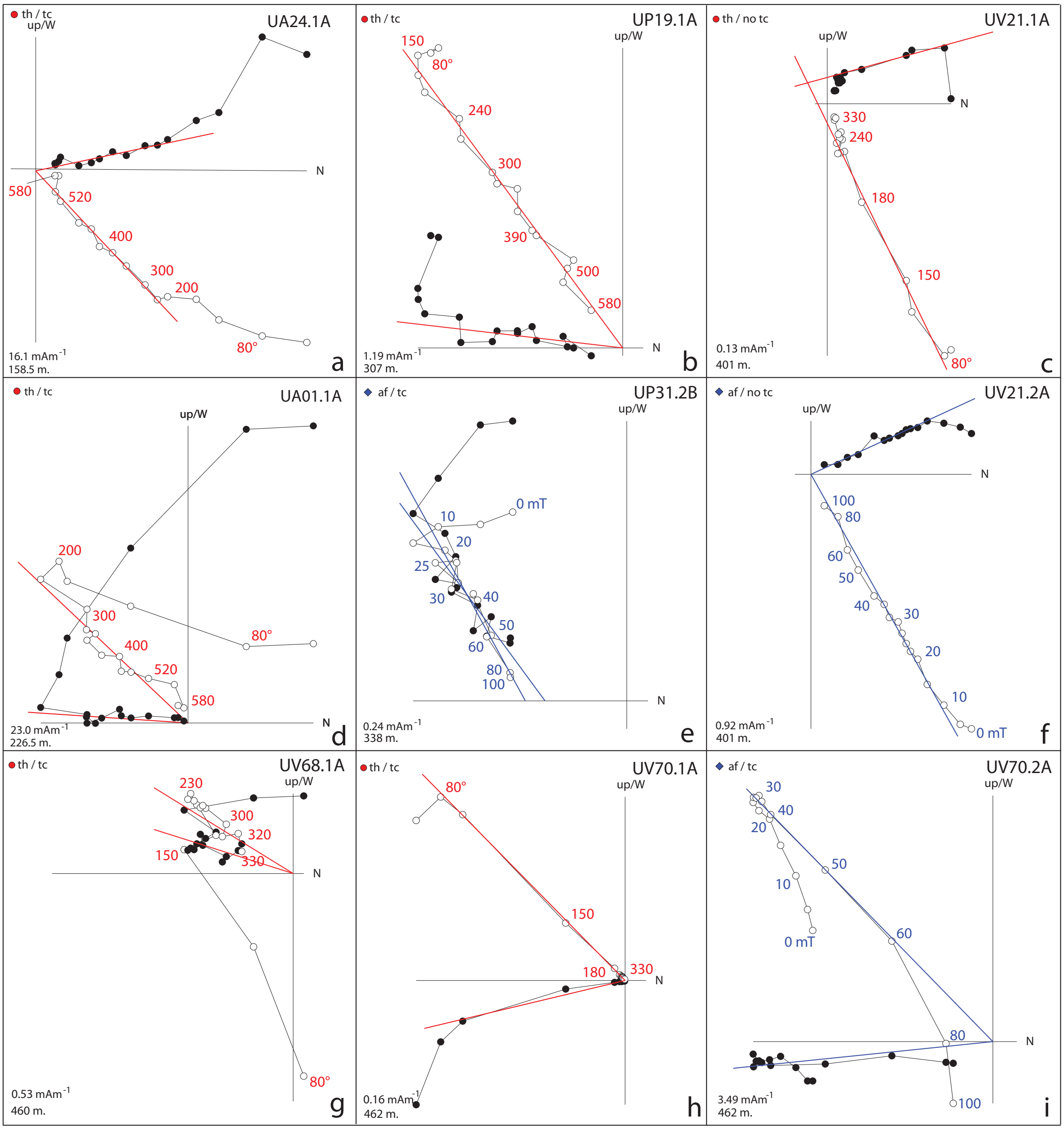

Figure 4: Thermal (th/red) and alternating field (af/blue) demagnetization diagrams of typical Lokbatan samples. Per sample: upper left) circles (diamonds) correspond to the symbols used in the magnetostratigraphy, tc (notc) samples are those presented with (without) tectonic correction; upper right) sample name; lower left) magnetic intensity at 250 °C and stratigraphic level (in meters). All diagrams are presented up/W. Values along vectors are temperature steps in °C (th) or af field in mT.

Site	N	dec	inc	k	$\alpha 95$
Lokbatan (normal)	61	350.8	34.2	13.8	5.1
Lokbatan (reversed)	70	198.1	-49.2	18.6	4.0
Lokbatan (PS, notc, low-T overprint)	68	3.5	50.9	27.2	3.7
Lokbatan (Akchagylian, notc, complete overprint)	43	5.3	54.0	20.5	5.6
Suçma (normal)	11	19.1	36.2	6.4	19.6
Suçma (reversed)	48	168.3	-56.1	17.2	5.1

Table 1: Results of NRM analysis from the Lokbatan and Suçma sections. N: number of samples, dec: declination, inc: inclination, k: precision parameter of Fischer (1953), $\alpha 95$: 95% cone of confidence.

mT (figure 4e). Complete demagnetization is not achieved in most samples, indicating an additional high-coercivity mineral.

Iron sulphides Also for the iron sulphide group a low temperature overprint is removed for temperatures up to 200-250°C (see figure 4g), further heating reveals a second component with a rapid decay up to 300-350°C. At these temperatures intensity (and susceptibility) starts to increase, due to the formation of new magnetic minerals. This type of magnetization is only found in the Akchagylian, intensities are generally low. Due to the high coercivity of the samples AF-demagnetization was not able to isolate a primary component.

Given the rapid decay between 280 and 330°C and the presence of gyroremanence during AF-demagnetisation (Fig. 4i) the mineral carrying the remanence is most likely greigite. Further (rock-magnetic) measurements should be undertaken to confirm this assumption.

3.2.2 Suçma

Main Suçma Section Most samples from the Suçma section are typified by one kind of demagnetization behaviour. A low-T component is removed at temperatures below 250°C, which accounts in half of the samples for a large part of the NRM (as much as 75%). Samples are generally completely demagnetized at either 500°C or at 600°C (see figure 5). Due to the relatively steep dip of the bedding (60-70°) a clear distinction can be made between primary normal directions and a pdf-overprint of the samples (see figure 5c). Initial intensities range between 2 and 100 mAm^{-1} and show a generally decreasing trend section-upwards. Based on the temperatures to which the samples were heated, the main magnetic carrier is an iron-oxide, most likely magnetite.

Suçma ash-section Demagnetization of the reverse oriented basal ash removes an overprint at temperatures of 200 to 250°C, at temperatures between 300 and 600°C a second, primary component is isolated, similar to the main Suçma section. The upper, normal-oriented ash shows a small overprint for temperatures up to 100°C, but is hard to distinguish due to the low bedding dip of only 20°.

3.3 Magnetostratigraphy

3.3.1 Lokbatan

Two polarity zones are found in the Lokbatan section, normal for the lower part, reversed for the upper part (see figure 6). At the PS-Akchagylian boundary, the magnetic intensity of the samples decreases abruptly, where in the PS it has a mean of 28 mAm^{-1} after being heated to 250°C, this is reduced to a mean of 0.24 mAm^{-1} in the Akchagylian. Initial susceptibility decreases an order of magnitude. Half the samples from the Akchagylian show only what is interpreted as secondary present-day overprint. They are completely demagnetized at temperatures between 200 and 250°C, and no primary component of the NRM can be identified. Figure 4c and f show demagnetization diagrams for both thermal and alternating field demagnetization of these samples, both without tectonic correction. Using the statistical Vandamme cut-off (Vandamme, 1994), the mean declination and inclination of both the low-T component of the PS samples and the completely overprinted Akchagylian samples plot close to the expected direction for the geocentric axial dipole (GAD) field near Baku (inc: 59° 17'). These Akchagylian samples are thus not taken as the ChRM but represent a later, secondary overprint and are thus not used in the magnetostratigraphy.

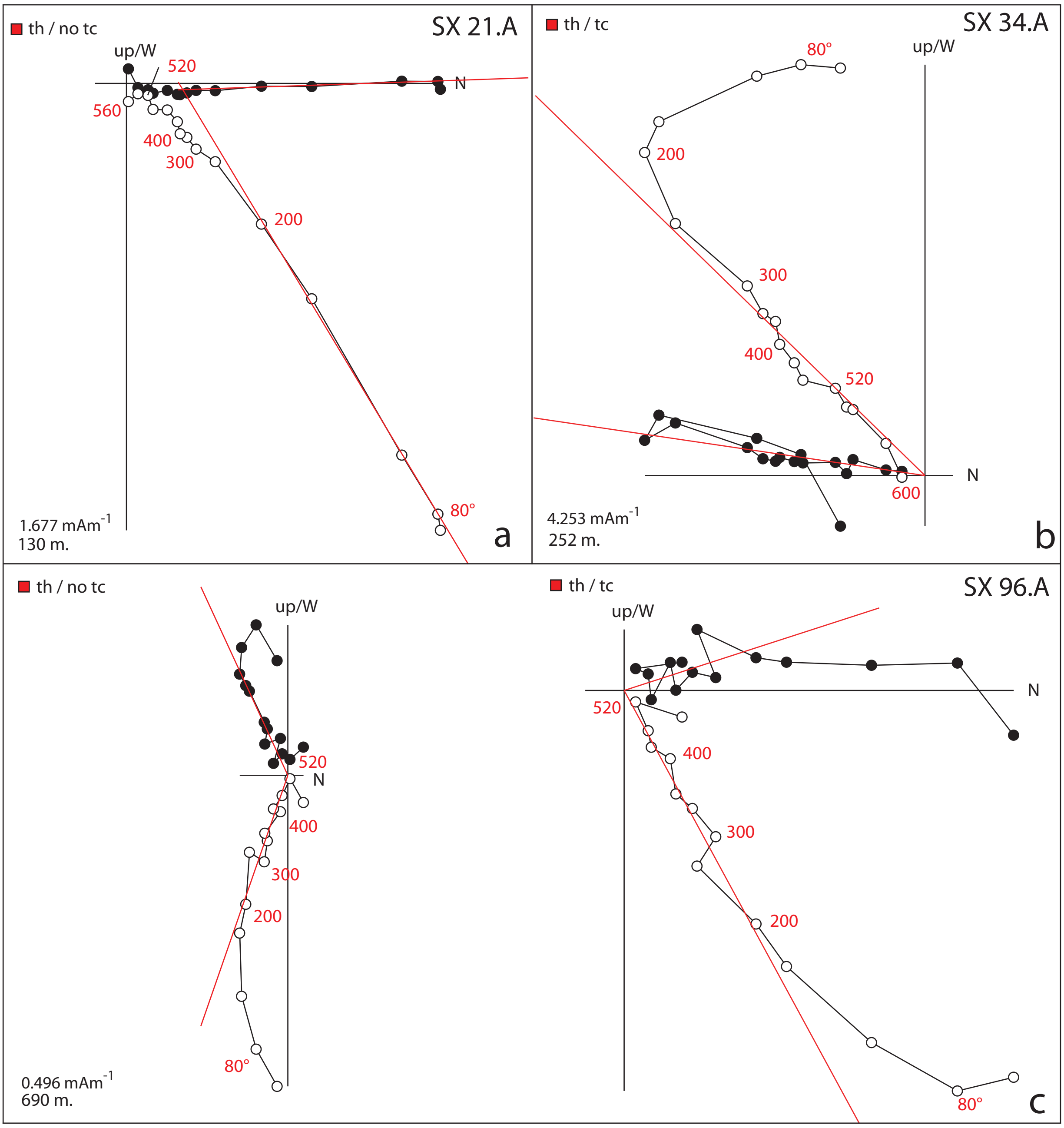

Figure 5: Thermal demagnetization diagrams of the Suçma section. Key similar to figure 4. Red squares in the upper left corner represent interpreted hand-samples.

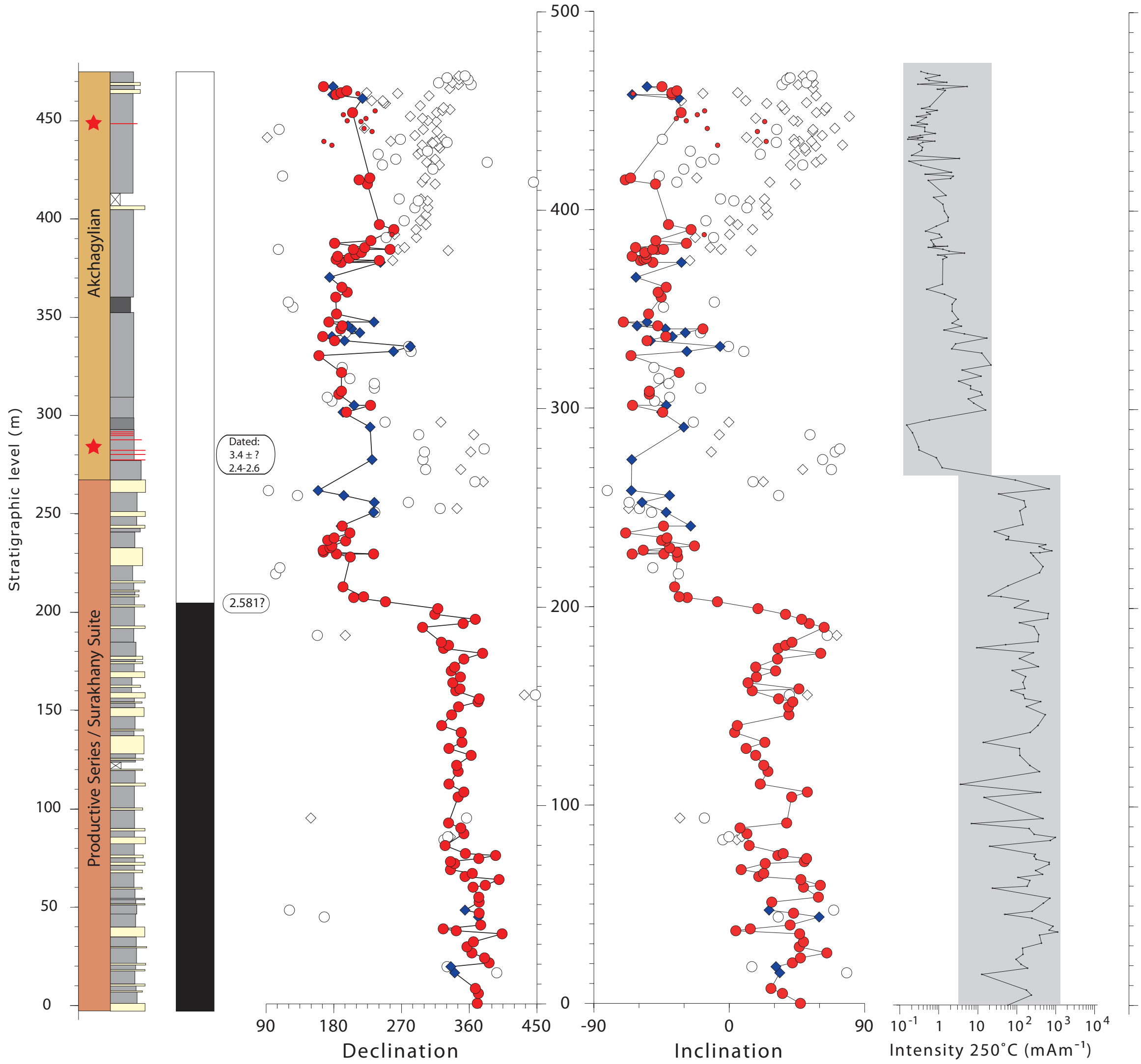

Figure 6: Magnetostratigraphy for the Lokbatan section, from left to right: stage names and (simplified) lithostratigraphy, in grey (yellowish) clays (sands), in red are ashes; interpreted polarity (black: normal, white: reverse); measured declination; measured inclination; magnetic intensity @ 250 °C; room for biostratigraphic results. Solid dots (diamonds) are reliable th (af) directions, open dots (diamonds) overprinted th (af) directions.

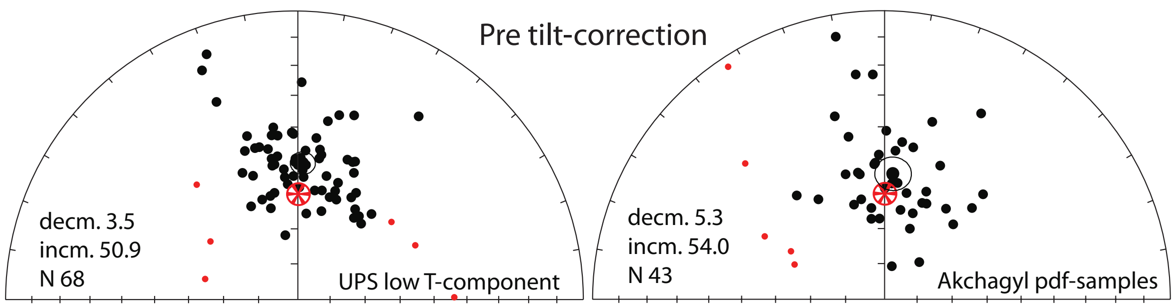

Figure 7: Equal area plots of the low temperature component of the PS and the Akchagylian samples with a complete overprint. Both are presented without tectonic correction, small red dots are directions that lie outside the Vandamme cut-off. Red stars are the GAD-direction for Azerbaijan.

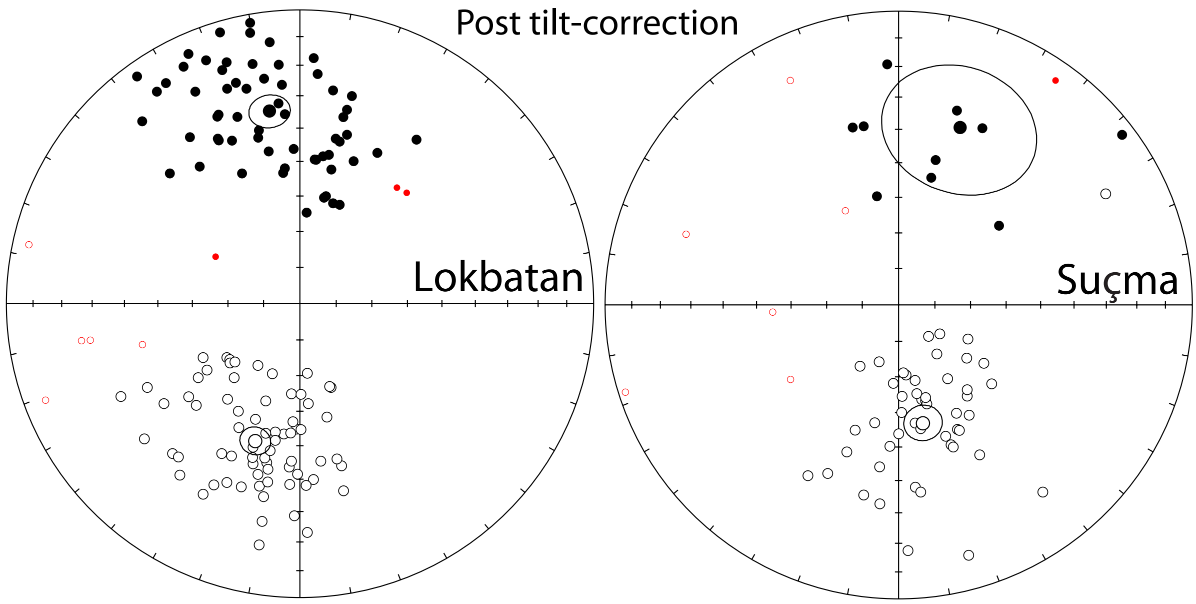

Figure 8: Equal area plots of the ChRM of samples from the Lokbatan and Suçma sections. Solid (open) dots: downward (upward) projections.

Reversal tests were performed on the reversals, which turned out to be negative for both sections (Lokbatan: $\gamma = 25.1 \leq \gamma_c = 6.1$, Suçma : $\gamma = 28.7 \leq \gamma_c$ 20.1). In Lokbatan this can be related to the low intensity of the Akchagylian samples, in the Suçma section due to the low number of normal oriented samples (see table 1 and fig 8).

3.3.2 Suçma

In the 900 meter long Suçma section five polarity zones are interpreted, two long reverse periods, with three short normal intervals at the base, halfway and at the top (see figure 9). Both oriented handsamples (squares) and drilled cores (circles) show the same polarities at given intervals (e.g. around meter 350) and can be used for the magnetostratigraphy. Completely overprinted samples are found in both handsamples and drilled cores, are spaced equally throughout the column and represent 20% of the samples.

The short Suçma section has a lower reversed part and an upper normal part (figure 10). Given the normal orientation of both the ash-layer in the main section and the top layer in the short section, these two should be the same layer. Having established a correlation between the two Suçma sections, the short section is ignored for the rest of the discussion.

3.4 Biostratigraphy

The biostratigraphic data of the sections are only available as preliminary results, which are summarized in the following section. In addition to our preliminary results, biostratigraphic work from other papers on outcrops in the Caspian basin of similar age is given.

- M. Stoica pers. comm., 2010: My first view the Akchagylian seams to be equivalent of Romanian stage (Dacian basin) that starts at 3.8 Ma.

- Ostracod-abundance in Lokbatan sections:

  In the uppermost part of the Productive Series ostracods are almost absent, with only some shell-fragments present. At meter 300 (35 meters into the Akchagylian) the number of ostracods starts to increase. Significant numbers of ostracods and microfossils have been found in this lower part (up to 350 m.). Higher levels have not yet been sampled.

- Preliminary results of ostracod species found in multiple sections near Baku (Pontian to Apsheronian regional stages):

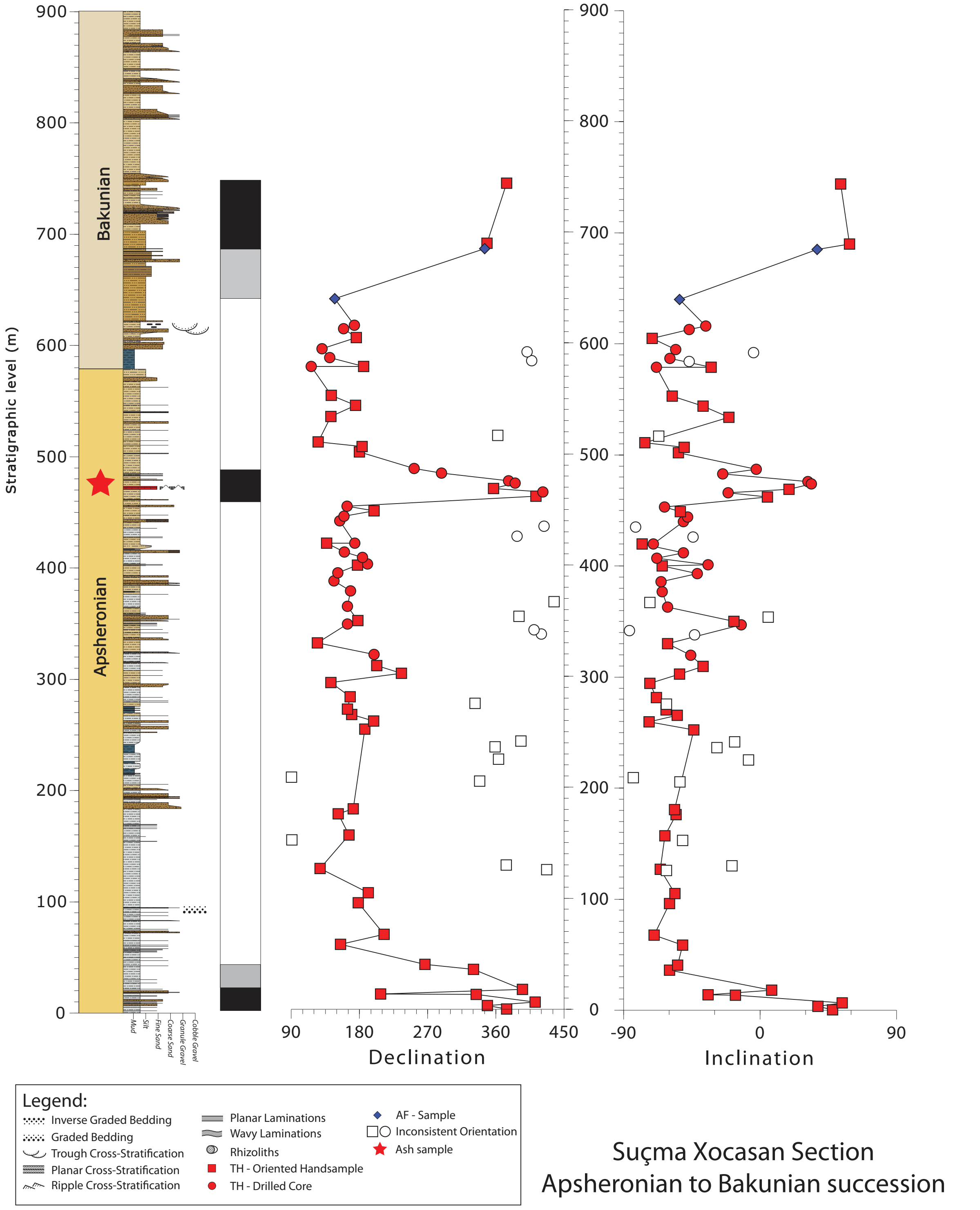

Figure 9: Suçma magnetostratigraphy, columns left to right: stage names and lithostratigraphy; interpreted polarity zones (black: normal, white: reversed); declination; inclination.

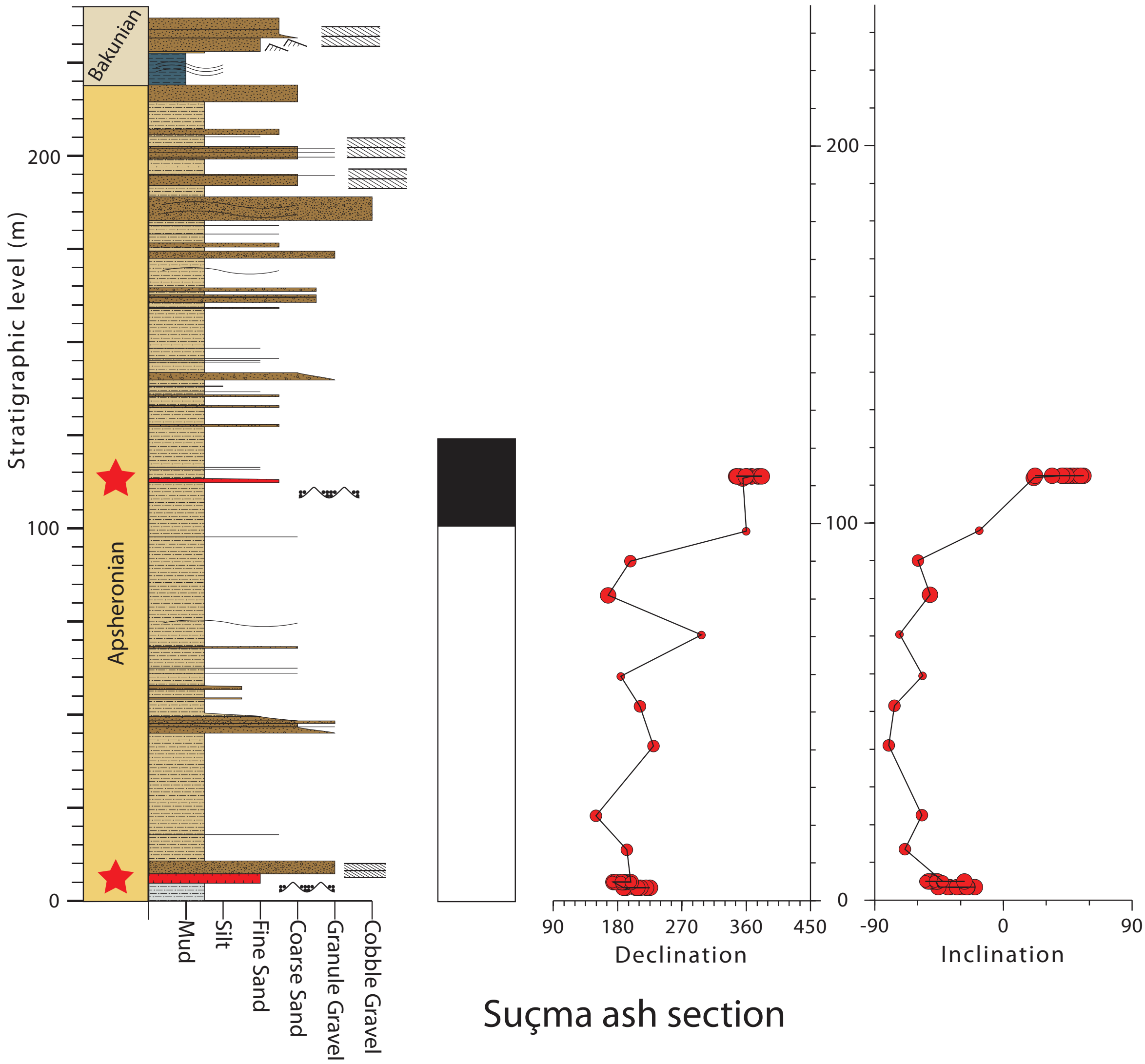

Figure 10: Suçma ash section magnetostratigraphy, from left to right similar to 9.

Candona sp. ex gr C. neglecta Sars; Candona (Caspiocypris) stevanovici Krstic; Caspiolla lobata (Zalany); Caspiolla pseudoacronasuta sp. n.; Pontinella acuminata (Zalanyi);Cytherissa naphtatscholana Liv.; Cythere multituberculata Liv.; Leptocythere picturata Liv.; Leptocythere nota sp. n.; Leptocythere pocornyi sp. n.; Leptocythere virgata sp. n.; Leptocythere (Amnicythere) accicularia sp n.; Leptocythere cf. scabrida Suz. In litt.: Leptocythere pseudoparwula sp.n.; Limnocythere ornamentata sp.n.; Amnicythere propinqua (Livental); Amnicythere sp. (ex gr A. ultima ultima); Loxoconcha sp.6; Loxoconcha carinata Lienenklaus

- Ostracod species from Pontian to Apsheronian, J.M. Khalilov (1946):

  Upper Pontian species not found in the Productive Series: Loxoconcha djaffarovi, Leptocythere paebacuana, Leptocythere. Avena, Leptocythere. Rosalinae etc.

  New species in the Productive Series: Iliocypris Brady, Limnocythere luculenta Liv., Cythere balanchica Chalil., Cythere Chalil delta etc.

  Ostracod species found near the boundary between Productive Series and Akchagylian: Canodona abichi Liv., Canodona run (Muller), Liv Leptocythere bicornis., Liv Leptochythere palimpsest. and forams: Cassidulina ex gr. Crassa Orb., Discorbis multicameratus Chutz.

  Species that continued into the Akchagylian and Apsheronian: Loxoconcha Eichwalde; Loxoconcha petasus, Cyprideis littoralis etc.

- On ostracods from Jones and Simmons (1996):

In Azerbaijan, the Akchagylian (Akchagyl Suite) contains a diverse marine ostracod and molluscan fauna. On the Apsheron Peninsula, it can be divided into three units on the basis of ostracods. Freshwater forms (Candona, Eucypris, Ilyocypris, Limnocythere) characterise the lower unit, marine and quasi-marine forms the middle and upper units.

- In Jones and Simmons from Semenenko and Lulieva (1982):

  Stratigraphically significant calcareous nannofossils recorded from the Akchagylian include

  1. Discoaster brouweri (NN8? - NN18) (no younger than 1.89 Ma)
  2. D. pentaradiatus (NN9? - NN17) (no younger than 2.33-2.43 Ma)
  3. Reticulofenestra pseudoumbilica (NN7? - NN15).

3.5 Glacial-relict species

A small part of the present species in the Caspian Sea are interpreted to have an Arctic origin, among them several crustaceans (Audzijonite et al., 2006, Vainola et al., 2008), fishes and the Caspian seal (Palo and Vainola, 2006). Since there is no connection with the Arctic ocean at present their origin remains uncertain. Three hypotheses for their presence exist. The first hypothesis regards the species as a Miocene relict, which was the last time connection with the Arctic Basin existed (McLaren, 1960). An alternative is an origin related to the Late Pleistocene overflow of pro-glacial lakes (Davies, 1958).

Based on genetic research, recent studies propose a new hypothesis for the age of these species. For example, divergence between Caspian and Arctic seals are to distant to have a Late Pleistocene age, but to close for a Miocene origin (Palo and Vainola, 2006). A late Pliocene to early Pleistocene age of 2-3 Ma is proposed for the origin of the Caspian seal. Work on crustaceans indicate multiple moments of connection during the past 2 Myr (Grigorovich et al., 2003).

4 Magnetostratigraphy

The magnetostratigraphies obtained for the Lokbatan and Suçma sections were correlated to the Geomagnetic Polarity Time Scale (GPTS) of Lourens et al. (2004). Figure 11 shows the correlation of the sections with the GPTS and the oxygen isotope record from Lisiecki and Raymo (2005). Table 2 shows the existing ages and the revised ages supported by our magnetostratigraphic work.

The Suçma section provides a good correlation with the GPTS with five polarity zones, three normal, two reverse. When the existing correlation of the base Bakunian close to the Matuyama/Brunhes (M/B) reversal (0.780 Ma) is taken into account (Jones and Simmons, 1996), a correlation between the Olduvai and the Brunhes is the only logical correlation (figure 11).

Mitchell and Westaway (1999) favoured a correlation of the lower Apsheronian with the Cobb Mt. cryptochron. This does not agree with the Suçma magnetostratigraphy, since this would imply an increased sedimentation rate for the lower part to two-and-a-half times the rate of the upper part of the section, of which no evidence is found in the field. The correlation with the Olduvai is thus favoured, the Suçma section thus stretches into the Olduvai subchron (1.8 Ma). Since this is not yet the base of the Apsheronian, the lower boundary is older than 1.8 Ma. The Suçma section spans more than a million years, mainly the upper part of the Matuyama chron (C1r), the base of the current section is placed in the Olduvai subchron (C2n, 1.770-1.950 Ma), the normal period halfway in the section is interpreted as the Jaramillo subchron, and the uppermost normal polarity horizons as the Brunhes chron (C1n). The exact position of the M/B reversal is unclear since it is in 40 meters of section that was not sampled, which puts an uncertainty on the Bakunian transgression.

The single reversal in Lokbatan (N-R) has a number of correlation options, top Gauss at 2.581 Ma (C2An.1), base Kaena (C2An.1r, 3.116 Ma), base Mammoth (C2An.2r, 3.330 Ma) and top Cochiti at 4.187 Ma (C3n.1n), given the basal age of the Kimmerian is at 5.5 Ma. Base Mammoth and base Kaena result in unrealistic sedimentation rates for the sampled Akchagylian (a minimum of 3.2 m/kyr and 2.2 m/kyr respectively), top Cochiti calls for a decrease in sedimentation rate from 400 cm/kyr to 20 cm/kyr at the Productive Series-Akchagylian boundary. In Lokbatan the lower half of the Akchagylian has been sampled (figure 12), which further supports a correlation to the Gauss/Matuyama (G/M) boundary. The favoured scenario for the Lokbatan reversal is therefore a correlation with the G/M boundary, which fits the age for the ash layers at 2.4-2.6 Ma by Groves et al. (1996). A relatively constant sedimentation rate is the result for the entire succession in the Caspian Basin, as is illustrated in figure 13. Since at this

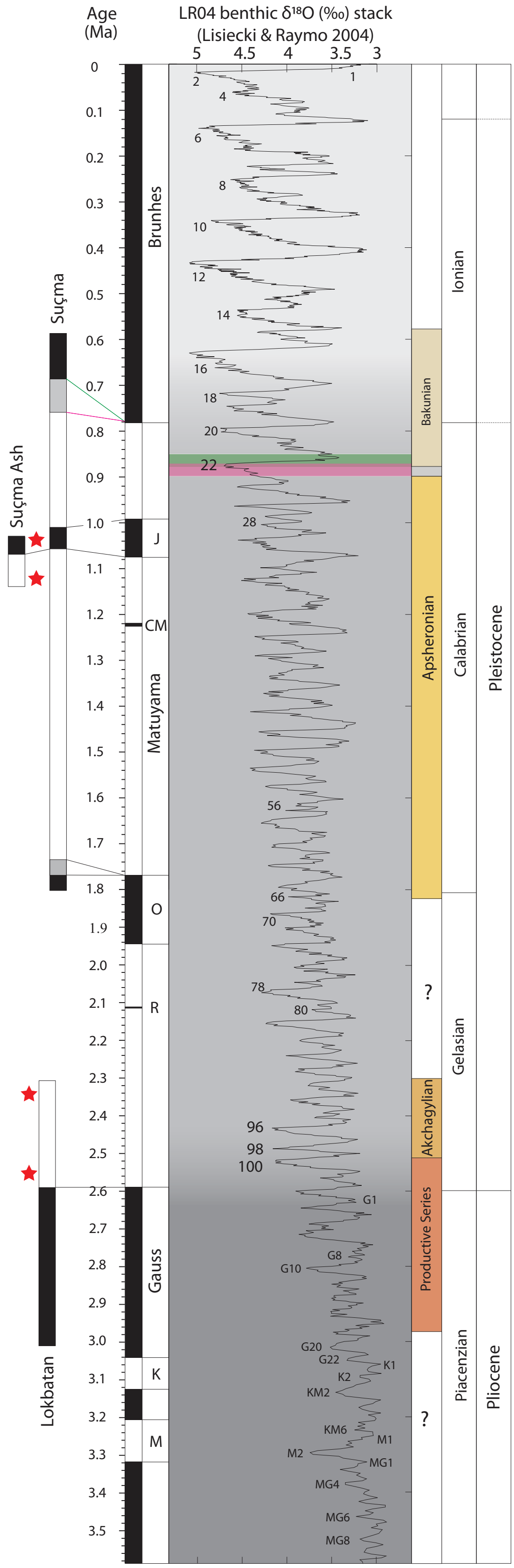

Figure 11: Magnetostratigraphy correlation and δ^{18}O curve. From left to right: Polarity signal of sampled sections; age in Ma; GPTS and (sub-) chron names (J: Jaramillo, CM: Cobb Mt., O: Olduvai, R: Reunion, K: Kaena, M: Mammmoth); δ^{18}O curve with some marine isotope stage plotted, shading refers to pre-Pleistocene, lower Pleistocene and middle/upper Pleistocene; Caspian regional stage names with boundaries according to new ages; Mediterranean stages; Neogene epochs.

	Jones & Simmons (1996)	This work & Krijgsman et al. (2010)
Bakunian	0.7	0.88±0.01
Apsheronian	1.6	1.8-2.0 (?)
Akchagylian	3.4	2.5 (?)
Kimmerian Productive Series	5.5	5.6±0.1
Pontian	7	6.04±0.01

Table 2: Existing Caspian Basin timescale and proposed revision, lower boundary ages are given (in Ma).

moment the other scenarios could in theory still apply, an alternative correlation (top Cochiti) is still presented in the general geological map of the Lokbatan outcrop (figure 12).

5 Discussion

5.1 Revision of Caspian Basin timescale

Table 2 summarizes the earlier proposed and revised ages for the Caspian Basin regional stages, the Bakunian, Apsheronian and Akchagylian are from this study, the Kimmerian (Productive Series) and Pontian are based on recent work in the Euxinian and Dacian basins (Krijgsman et al., 2010). The most significant change is the reassignment of the base Akchagylian above the G/M boundary, around 2.5 Ma. The duration of the Akchagylian is reduced to around 500-700 kyr, depending on the age of the top boundary, which is significantly shorter than the 1.8 Myr in the existing timescale. Decreasing the duration of the Akchagylian increases the duration of the Kimmerian / Productive Series to 3.0 Myr, decreasing the sedimentation rate of the Productive Series in the South Caspian Basin to 195 cm/kyr, based on stage-thicknesses by Allen et al. (2002).

In existing literature a transgression at 2.5 Ma has widely been recognized in distal parts of the basin (Don, Dnieper, Dniester, Volga (Matoshko et al., 2004) and Amu Darya (Abdullayev, 2000)), but this has always been interpreted as the third and final Akchagylian transgression. This work suggests that this is not the case, a correlation with the base Akchagylian transgression is more likely. Alternatively, the base Akchagylian in Azerbaijan is not the time-equivalent of other regions.

The correlation between the Caspian and Black Sea basins needs also to be revised based on our new results. The Akchagylian was correlated 1:1 to the entire (time-equivalent) Kuyalnikian regional stage in the Black Sea basin (e.g. Jones and Simmons (1996)), which will need to be changed to either a part of the Kuyalnikian or this also needs to be assigned a shorter duration. A detailed magnetostratigraphy for these stages in the Black Sea is required to solve this problem. Similar work should be done to establish a correlation with the Aral Sea in the east.

Another subject of interest is the age of folding in the offshore Caspian Basin, which is placed in the lower part of the Akchagylian at the first observed stratal thinning over folds (Devlin et al., 1999). This is the moment hydrocarbon traps start forming, which is now lowered to 2.5 Ma, or even younger if the unconformity in the upper part of the Lokbatan section is taken as this moment.

5.2 'Glacio-marine' transgressions

Given the abrupt decrease in intensity found in Lokbatan, which is most logically explained by an instantaneous increase in waterdepth, it is likely that the Akchagylian transgression occurred geologically instantaneous, rather than gradual. The age of the PS-Akchagylian boundary is based on our results above the G/M boundary, which coincides with the interval MIS 100, 98 and 96. These cold intervals together form the moment of first major land-based glaciation on the northern hemisphere (Matthiessen et al., 2009, Knies et al., 2009, Lourens et al., 2010). The age of the transgression at the base Bakunian before or during MIS 22 places it in the early phase of the mid-Pleistocene transition, another period of major northern hemisphere glaciation.

Correlation of Caspian highstands with eustatic highstands as proposed by Jones and Simmons (1996) is not supported by our new results. Since sea-level during glaciations is low, an overflow of marine waters due to high eustatic levels is unlikely. The model for Late Pleistocene overflow of ice-dammed lakes due to deglacial melting and a reversal of the drainage direction from Scandinavia to Siberia seams a more appropriate model (Mangerud et al. (2001), figure 14 for a simplified model). Timing of both

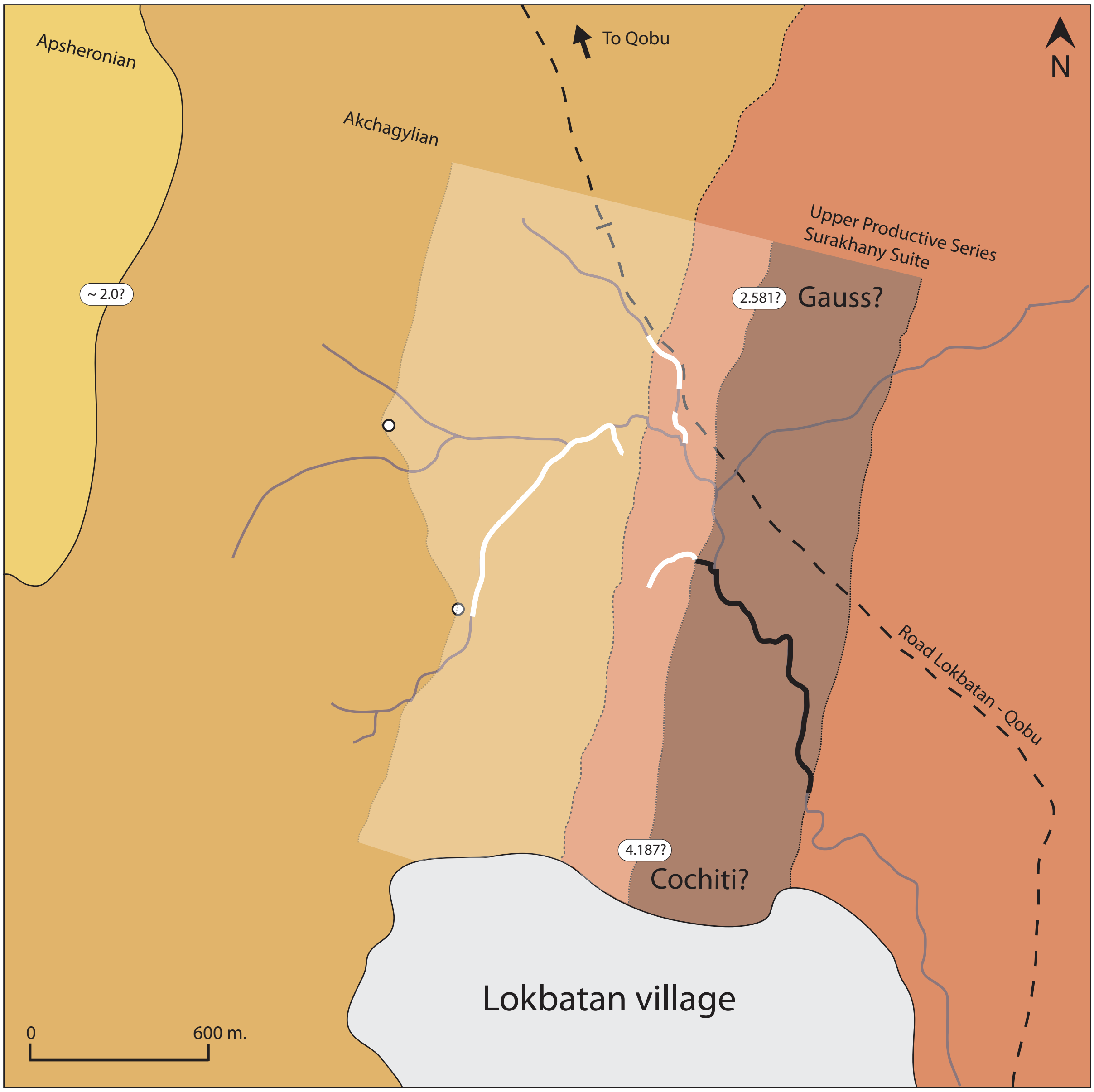

Figure 12: Geological map of the Lokbatan section in which grey lines indicate the general drainage pattern. The white and black lines indicate the polarity pattern along the sampled outcrop, shades of white and black the extrapolation of the polarity across the outcrop. Indicated are the two scenarios for the age of the section. The two white dots in the Akchagylian represent the same slumped interval identified at these two locations, which mark the top of the sampled section.

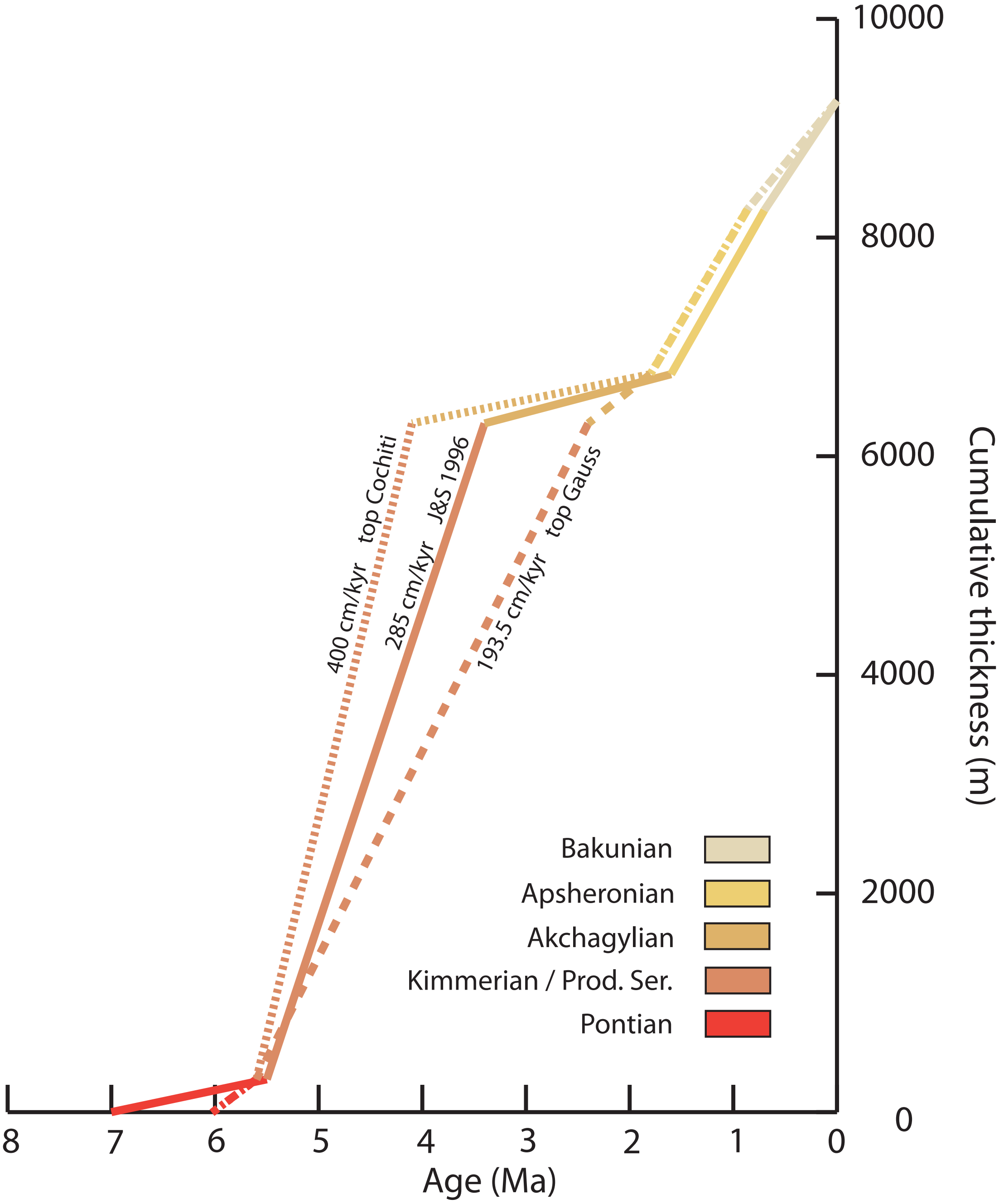

Figure 13: Sedimentation rate for three scenarios of duration of Caspian Basin stages. J&S 1996 represents the work by Jones and Simmons, top Gauss and top Cochiti are the two possible scenarios based on this work. Sedimentation rates based on thicknesses reported by Allen et al. (2002) for the South Caspian Basin.

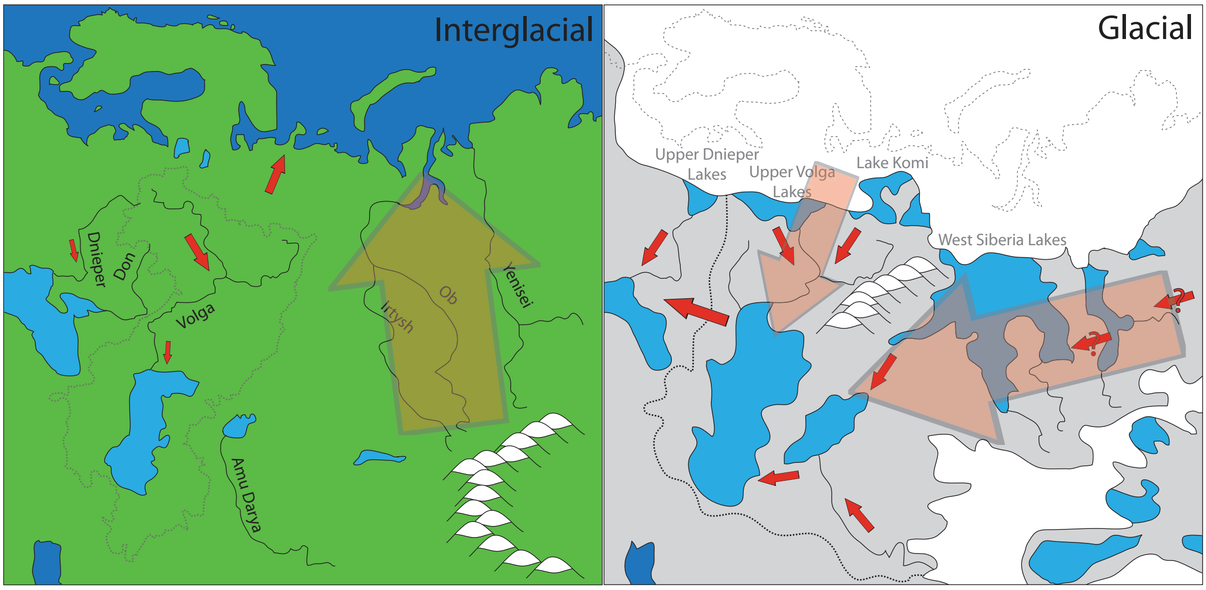

Figure 14: Model of the glacial-interglacial drainage hypothesis as used for the Akchagylian transgression.

the Akchagylian and the Bakunian transgressions during major cold periods in the Pleistocene and the instantaneous nature of the transgressions favours this hypothesis. Transgression of the Caspian Sea during (or just before) maximum glaciation is not likely since available water will then be locked in the ice-sheet and the climate is more arid.

The presence of species with an Arctic origin proves the connection with the Arctic Basin. The Akchagylian transgression coincides with the proposed age for the origin of the Caspian seal of 2-3 Ma (Palo and Vainola, 2006). Furthermore, the northern origin of the Akchagylian transgression explains the pathway by which the seals could have come into the Caspian Sea.

Alternating volcanic and glacial layers are found in the highest parts of the Greater Caucasus (Mt. Elbrus), which are interpreted to started to have formed before 2.8 Ma (Milanovsky, 2008). Deglaciation in the hinterland of the Amu Darya in the east is also likely to increase discharge significantly, but the extent of glaciations at that time remains unclear. This glacial water cannot explain the typical vast brackish to semi-marine Akchagylian fauna, and is thus not likely to be the most important contributor to the transgression. In the Aral Sea basin also salt accumulations are reported, which are interpreted to be the result of major evaporation after the marine Akchagylian transgression (Boomer et al., 2000). The northern connection could explain the typical fauna and these salt accumulations. Finding typical (Arctic) cold-water species immediately after the Akchagylian transgression in Lokbatan could prove this hypothesis, which should be the focus of future biostratigraphic work.

6 Conclusions

This work presents the first magnetostratigraphic work on long sections in time and space in the Caspian and Kura Basins of Azerbaijan. In time spanning from the uppermost Productive Series (Kimmerian) to the Bakunian regional stages. The top of the Productive Series has (most likely) an age of 2.5 Ma (G/M boundary), top Akchagylian around 1.8-2.0 Ma (older than top Olduvai, C2n) and the top Apsheronian an age of 0.88 Ma (in the middle of C1r between top Jaramillo and base Brunhes). The resulting average sedimentation rate for the South Caspian Basin is high and relatively constant around a rate of 1.9 m/kyr since the moment of isolation of the basin around 5.5 Ma. The duration of the Productive Series is increased to 3.0 Myr, while the duration of the Akchagylian is lowered to 0.5-0.7 Myr.

Both at the top Productive Series and the top Apsheronian boundaries a marked transgression is found, while both boundaries are now in time placed during cold periods in the Pleistocene (top Productive Series at MIS 100-96, top Apsheronian at MIS 22). A link between periods of extensive land-based glaciation and these transgressions thus forms the best explanation.

We therefore propose a hypothesis where overflow of ice-dammed lakes into the Caspian Sea cause the transgressions, which is based on existing models for Late Pleistocene proglacial discharge in the West Siberia Basin. The existence of species with an Arctic origin at this time would provide support for this theory. This hypothesis is different from the existing theory that water should have come via a (yet unknown) passage from the Mediterranean Sea. Further work to see how far the effect of these glacio-marine transgressions can be traced (Black Sea or even Mediterranean Sea) should be undertaken in the future.

References

N.R. Abdullayev. Seismic stratigraphy of the upper pliocene and quaternary deposits in the south caspian basin. *Journal of Petroleum Science and Engineering*, 28:207–226, 2000.

V. Abreu and D. Nummedal. Miocene to quaternary sequence stratigraphy of the south and central caspian basins. In P.O. Yilmaz and G.H. Isaksen, editors, *Oil and Gas in the Greater Caspian Area: AAPG Studies in Geology 55*, pages 65–86. 2007.

M.B. Allen, S. Jones, A.D. Ismail-Zadeh, M.D. Simmons, and L. Anderson. Onset of subduction as the cause of rapid pliocene/quaternary subsidence in the south caspian basin. *Geology*, 30:775–778, 2002.

S.A. Arkhipov, J. Ehlers, R.G. Johnson, and H.E. Wright. Glacial drainage towards the mediterranean during the middle and late pleistocene. *Boreas*, 24:196–206, 1995.

A. Audzijonite, M.E. Daneliya, and R. Vainola. Comparative phylogeography of ponto caspian mysid crustaceans: isolation and exchange among dynamic inland sea basins. *Molecular Ecology*, 15:2969–2984, 2006.

I. Boomer, N. Aladin, I. Plotnikov, and R. Whatley. The palaeolimnology of the aral sea: a review. *Quaternary Science Reviews*, 19:1259–1278, 2000.

M. Brunet, M.V. Korotaev, A.V. Ershov, and A.M. Nikishin. The south caspian basin: a review of its evolution from subsidence modelling. *Sedimentary Geology*, 156:119–148, 2003.

I.S. Chumakov, S.L. Byzova, and S.S. Ganzey. Meotian to pontian geochronology of eastern paratethys. *Doklady Akademia Nauk SSSR*, 303:178–181, 1988.

J.L. Davies. Pleistocene geography and the distribution of northern pinnipeds. *Ecology*, 39(1):97–113, 1958.

W.J. Devlin, J.M. Cogswell, G.M. Gaskins, G.H. Isaksen, D.M. Pitcher, D.P. Puls, K.O. Stanley, and G.R.T. Wall. South caspian basin: Young, cool and full of promise. *GSA Today*, 9(7):1–9, 1999.

H.J. Dumont. The caspian lake: History, biota, structure, and function. *Limnology and Oceanography*, 43(1):44–52, 1998.

S.S. Egan, J. Mosar, M. Brunet, and T. Kangarli. Subsidence and uplift mechanisms within the south caspian basin: insights from the onshore and offshore azerbaijan region. *Geological Society, London, Special Publications*, 312:219–240, 2009.

R.A. Fischer. Dispersion on a sphere. *Proceedings of the Royal Society of London, Series A*, 217:295–305, 1953.

A.M. Forte, E. Cowgill, T. Bernardin, O. Kreylos, and B. Hamann. Late cenozoic deformation of the kura fold-thrust belt, southern greater caucasus. *GSA Bulletin*, 122(3/4):465–486, 2010.

S.R. Fowler, J. Mildenahll, S. Zalova, G. Riley, G. Elsley, A. Desplanques, and F. Guliyev. Mud volcanoes and structural development on shah deniz. *Journal of Petroleum Science and Engineering*, 28:189–206, 2000.

T. Green, N.R. Abdullayev, J. Hossack, G. Riley, and A.M. Roberts. Sedimentation and subsidence in the south caspian basin, azerbaijan. *Geological Society, London, Special Publications*, 312:241–260, 2009.

I.A. Grigorovich, T.W. Therriault, and H.J. MacIsaac. History of aquatic invertebrate invasions in the caspian sea. *Biological Invasions*, 5:103–115, 2003.

M.G. Grosswald. New approach to the ice age paleohydrology of northern eurasia. In G. Benito, V.R. Baker, and K.J. Gregory, editors, *Palaeohydrology and Environmental Change*. John Wiley and Sons Ltd., 1998.

J.R. Groves, J.A. Stein, A. Babazade, R.O. Koshkarly, and D.N. Mamedova. Biostratigraphic and isotopic evidence for determining rates of rock accumulation within the productive series of eastern azerbaijan. In *American Association of Petroleum Geologists, Symposium on Rapidly Subsiding Basins*, page (unpaginated), Baku, Azerbaijan Republic, 1996.

D.J. Hinds, E. Aliyeva, M.B. Allen, C.E. Davies, S.B. Kroonenberg, M.D. Simmons, and S.J. Vincent. Sedimentation in a discharge dominated fluvial/lacustrine system: the neogene productive series of the south caspian basin, azerbaijan. *Marine and Petroleum Geology*, 21:613–638, 2004.

R.W. Jones and M.D. Simmons. A review of the stratigraphy of eastern paratethys (oligocene-holocene). *Bulletin of the Natural History Museum (Geology Supplement)*, 52:25–49, 1996.

J.L. Kirschvink. The least-square line and plane and the analysis of paleomagnetic data. *Geophys. J. R. Astron. Soc.*, 62: 699–718, 1980.

C.C. Knapp, J.H. Knapp, and J.A. Connor. Crustal-scale structure of the south caspian basin revealed by deep seismic reflection profiling. *Marine and Petroleum Geology*, 21:1073–1081, 2004.

J. Knies, J. Matthiessen, C. Vogt, J.S. Laberg, B.O. Hjelstuen, M. Smelror, E. Larsen, K. Andreassen, T. Eidvin, and T.O. Vorren. The plio-pleistocene glaciation of the barents sea-svalbard region: a new model based on revised chronostratigraphy. *Quaternary Science Reviews*, 28:812–829, 2009.

W. Krijgsman, M. Stoica, I. Vasiliev, and V.V. Popov. Rise and fall of the paratethys sea during the messinian salinity crisis. *Earth Planet. Sci. Lett.*, 290(1-2):183–191, 2010.

L.E. Lisiecki and M.E. Raymo. A pliocene-pleistocene stack of 57 globally distributed benthic d18o records. *Paleoceanography*, 20, 2005.

L.J. Lourens, F.J. Hilgen, J. Laskar, N.J. Shackleton, and D. Wilson. The neogene period. In A.G. Smith, editor, *A Geological Time Scale 2004*, Cambridge, 2004. Cambridge University Press.

L.J. Lourens, J. Becker, R. Bintanja, F.J. Hilgen, E. Tuenter, R.S.W. Van de Wal, and M. Ziegler. Linear and non-linear responce of late neogene glacial cycles to obliquity forcing and implications for the milankovitch theory. *Quaternary Science Reviews*, 29:352–365, 2010.

J. Mangerud, V. Astakhov, M. Jakobsson, and J.I. Svendsen. Huge ice-age lakes in russia. *Journal of Quaternary Science*, 16(8):773–777, 2001.

A.V. Matoshko, P.F. Gozhik, and G. Danukalova. Key late cenozoic fluvial archives of eastern europe: the dniester, dnieper, don and volga. *Proceedings of the Geologists' Association*, 115:141–173, 2004.

J. Matthiessen, J. Knies, C. Vogt, and RR. Stein. Pliocene palaeoceanography of the arctic ocean and subarctic seas. *Philosophical transactions of the royal society A.*, 367:21–48, 2009.

I.A. McLaren. On the origin of the caspian and baikal seals and the paleoclimatological implication. *American Journal of Science*, 258:47–65, 1960.

E.E. Milanovsky. Origin and development of ideas on pliocene and quaternary glaciations in northern and eastern europe, iceland, caucasus and siberia. *Geological Society, London, Special Publications*, 301:87–115, 2008.

J. Mitchell and R. Westaway. Chronology of neogene and quaternary uplift and magmatism in the caucasus: constraints from k-ar dating of volcanism in armenia. *Tectonophysics*, 304:157–186, 1999.

L.A. Nevesskaya, I.A. Goncharova, L.B. Ilyina, N.P. Paramonova, and S.O. Khondkarian. The neogene stratigraphic scale of the eastern paratethys. *Stratigraphy and Geological Correlation*, 11(2):105–127, 2002.

J.U. Palo and R. Vainola. The enigma of the landlocked baikal and caspian seals addressed through phylogeny of phocine mitochondrial sequences. *Biological Journal of the Linnean Society*, 88(1):61–72, 2006.

S.V. Popov, I.G. Shcherba, L.B. Ilyina, L.A. Nevesskaya, N.P. Paramonova, S.O. Khondkarian, and I. Magyar. Late miocene to pliocene palaeogeography of the paratethys and its relation to the mediterranean. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 238:91–106, 2006.

S.V. Popov, M.P. Antipov, A.S. Zastrozhnov, E.E. Kurina, and T.N. Pinchuk. Sea-level fluctuations on the northern shelf of the eastern paratethys in the oligocene-neogene. *Stratigraphy and Geological Correlation*, 18(2):200–224, 2010.

A.D. Reynolds, M.D. Simmons, B.J. Bowman, J. Henton, A.C. Brayshaw, A.A. Ali-Zade, I.S. Guliyev, S.F. Suleymanova, E.Z. Ateava, D.N. Mamedova, and R.O. Koshkarly. Implications of outcrop geology for reservoirs in the neogene productive series: Apsheron peninsula, azerbaijan. *AAPG Bulletin*, 82(1):25–49, 1998.

J.L. Smale, T. Baylin, and Y. Shikhaliyev. Faulting and associated mud diapirism in the south caspian basin: implication for hydrocarbon trap development. In *SEG Annu. Meet. Expanded*, pages 589–591, 1997.

R. Vainola, J.D.S. Witt, M. Grabowski, J.H. Bradbury, K. Jazdzewski, and B. Sket. Global diversity of amphipods (amphipoda; crustacea) in fresh-water. *Hydrobiologia*, 595:241–255, 2008.

A.J. Van Velzen and J.D.A. Zijderveld. Effects of weathering on single domain magnetite in early pliocene marls. *Geophys. J. Int.*, 121:267–278, 1995.

D. Vandamme. A new method to determine paleosecular variation. *Phys. Earth Planet. Inter.*, 85:131–142, 1994.

I. Vasiliev, W. Krijgsman, C.G. Langereis, C.E. Panaiotu, L. Matenco, and G. Bertotti. Towards an astrochronological framework for the eastern paratethys mio-pliocene sedimentary sequences of the focsani basin (romania). *Earth Planet. Sci. Lett.*, 227:231–247, 2004.

J.D.A. Zijderveld. *A.C. demagnetization of rocks: analysis of results*. Developments in Solid Earth Geosciences Methods in Palaeomagnetism. Elsevier Publishing Company, Amsterdam, 1967.

L.P. Zonenshain and X. Le Pichon. Deep basins of the black sea and caspian sea as remnants of mesozoic back-arc basins. *Tectonophysics*, 123:181–211, 1986.

V.A. Zubakov. History and causes of variations in the caspian sea level: the miopliocene, 7.1-1.95 million years ago. *Water Resources*, 28(3):249–256, 2001.