Sediment petrography, mineralogy and geochemistry of the Miocene Islam Dağ Section (Eastern Azerbaijan): Implications for the evolution of sediment provenance, palaeo-environment and (post-)depositional alteration patterns

ANDRE BALDERMANN*†, ELSHAN ABDULLAYEV†, YELENA TAGHIYEVA†, ALASGAR ALASGAROV‡† and ZOHRAB JAVAD-ZADA†

*Institute of Applied Geosciences & NAWI Graz GeoCenter, Graz University of Technology, Rechbauerstraße 12, Graz, 8010, Austria
†Academician H. Aliyev Institute of Geography, Azerbaijan National Academy of Science, H. Javid St. 115, Baku, AZ1143, Azerbaijan
‡Geography Faculty, Baku State University, Academic Zahid Khalilov St. 23, Baku, AZ1148, Azerbaijan

Associate Editor – Catherine Reid

ABSTRACT

The reconstruction of regional long-term patterns recorded in marine sedimentary successions of the Eastern Paratethys is important in understanding the role of Cenozoic climate change and orogenic activity on the depositional environment and sedimentation dynamics in Western Asia. In this study, the environmental conditions in the early to middle Miocene (Islam Dağ section) in eastern Azerbaijan are elucidated using petrographic–mineralogical relations, detrital indicators, weathering indices and d13C and d18O signatures of organic-rich (total organic carbon: ca 3 to 6 wt. %) argillites. Sedimentary facies and chemical proxies (Na/K, K/Al, Si/Al, Ti/Al ratios, chemical index of alteration values) indicate arid conditions, reduced weathering rates in the hinterland and sediment deposition in an euhaline and poorly oxygenated deep-water basin during the early Miocene, followed by a shift to humid conditions, higher weathering rates and an oxygenated water column in the mid-early Miocene. Long-term aridification and deposition of gypsiferous and calcareous argillites under generally more oxygenated, euhaline to polyhaline conditions in a lacustrine or restricted shelf setting until the middle Miocene is evidenced by gradual changes in element ratios and the chemical index of alteration. Discriminant function analysis suggests the Russian Platform, drained by the Palaeo-Volga and Palaeo-Don river systems, to be the source area for the siliciclastic input throughout the Miocene, although a minor contribution of volcanogenic detritus and mafic components from the Greater Caucasus is possible. The C–S–Fe associations and increasing Fe/Al ratios towards the middle Miocene support the concept of continuous influx of detrital Fe and total organic carbon. The formation of ferruginous smectite from alteration of volcanic ash layers could have affected the preservation of total organic carbon and therefore the sedimentary C and Fe budget in the Eastern Paratethys basins. Palaeo-climatic reconstructions based on δ13C (−34.5 to −1.7‰ Vienna Pee Dee Belemnite) and δ18O (−34.7 to −4.8‰ Vienna Pee Dee Belemnite) records of authigenic carbonates should be made with great caution, as the pristine marine signatures may be affected by the oxidation of organic matter and meteoric diagenesis.
INTRODUCTION

In the terminal Eocene and early Oligocene the collision of the African–Arabian–Eurasian plates, a eustatic sea-level fall and the uplift of the Alpine fold belt resulted in the progressive isolation of the Alpine–Carpathian and Euxinic–Caspian basins from the Tethys Ocean, causing variations in biodiversity, hydrological regime and sedimentation dynamics from central Europe to western Asia (e.g. Baldi, 1980; Jones & Simmons, 1996; Feyzullayev et al., 2001; Popov et al., 2004, 2010; Sachsenhofer et al., 2015). Subsequent palaeo-oceanographic processes in the Crimea–Caucasian–Kopetdagh deep-water environments of the Eastern Paratethys Sea provided conditions suitable for the establishment of a thermohaline water stratification and estuarine water circulation pattern with recurrent periods of anoxia (Baldi, 1980; Golonka, 2004; Johnson et al., 2010). This is expressed by the deposition of ca 1000 to 1500 m thick, organic-rich clayey sequences of Oligo–Miocene age (the so-called ‘Maikop’ facies), which are source rocks for hydrocarbons of economic significance, for example, in eastern Azerbaijan (e.g. Feyzullayev et al., 2001; Guliyev et al., 2001; Johnson et al., 2010; Bechtel et al., 2013; Sachsenhofer et al., 2015). During the early to middle Miocene, a prominent change from deep-marine settings with fluctuating salinities into shallow-marine and evaporative regimes is traceable in the Euxinic–Caspian basins, resulting in the deposition of marly clays with intercalated limestone beds (Jones & Simmons, 1996; Popov et al., 2004, 2010; Abdullayev & Leroy, 2016).

Several studies have been published in the past describing sedimentary environments and facies, palaeo-geography and source rock potential of the Oligo–Miocene rocks from the Euxinic–Caspian basins (e.g. Jones & Simmons, 1996; Popov et al., 2008; Sachsenhofer et al., 2018). However, sedimentological, petrographic, mineralogical and (isotope) geochemical studies focusing on the characterization and reconstruction of the spatiotemporal evolution of depositional environments, palaeoclimate and diagenesis are still scarce. Recently, a chemostratigraphic correlation between different outcrops (Islam Dağ, Boyanata, Göytepe, Peri-küşkül, etc.) has been developed (Hudson et al., 2008, 2016; Johnson et al., 2010) utilizing redox-sensitive trace metals (V, Ni, Mo, U, etc.), biomarkers and chemical parameters (total organic carbon, δ13Ctot, δ13Corg, field γ-ray values, C–S–Fe associations, ratios of Fe/Al and Ti/Al, etc.). However, problems still persist with the age and lateral correlation of the Maikopian strata in eastern Azerbaijan, because of major lateral variability in the source rocks, lack of diagnostic microfaunal elements and inconsistencies in age dating of clayey deposits (Bechtel et al., 2014; Sachsenhofer et al., 2018). Until recently, the stratigraphy of the Maikopian strata is still poorly constrained (Washburn et al., 2018).

The Islam Dağ section (eastern Azerbaijan) is a key area for investigating the impact of local tectonic activity, basin evolution and regional-scale response of the Eastern Paratethys to long-term Cenozoic global cooling, because this location exhibits an almost complete succession of offshore marine argillaceous rocks of early to middle Miocene age (Washburn et al., 2018). This study presents a novel mineralogical, major/minor elemental and δ13C and δ18O dataset of the argillaceous rocks from this famous study site, and discusses implications for the provenance of sediments, evolution of climate, salinity, redox conditions and post-depositional processes. The obtained results are of great significance for reconstructing climate change in eastern Azerbaijan on a regional scale and for correlating the marine, organic-rich succession with other areas (for example, the Vienna Basin, Black Sea and Mediterranean Sea) of the Paratethys in the Miocene.

GEOLOGICAL SETTING AND LITHOSTRATIGRAPHY

The sedimentary rocks from the Islam Dağ section are exposed in several outcrops alongside the Islam Dağ (‘dağ’ means mountains) range, which is located about 50 km north-west of Baku (Azerbaijan) within the Gobustan–Absheron depression of the South Caspian Basin Province (Fig. 1). This location exhibits a
sedimentary succession of argillaceous rocks of late Oligocene to middle Miocene age (Fig. 2). The lowermost part of this section, comprising late Oligocene argillites of greyish colour (John-
son et al., 2010), is currently not exposed due to overburden by local colluvium. The bottom part of the profile comprises massive (metre-scale) and structureless argillites of greyish-black colour that are intercalated with thin (few centimetres) siltstone lenses. These organic-rich sequences have been assigned to the Oligo–Mi-
ocene Maikop facies and were interpreted as deposits of a ‘deep-water’ depression under dys-
oxic to anoxic conditions (Popov et al., 2004, 2008). This unit is overlain by greyish-black to yellowish-green (when oxidized) argillites, which are thought to have been deposited in a restricted shelf setting during the Miocene (Rögl, 1999). Due to sea-level fluctuations and uplifting of the Russian Platform, the Ural and the Kazak-
khstan Highs in the north and the Lesser Caucasus, Elburz and Kopetdagh mountain system in the south, a strong differentiation of the deposi-
tional environment of the South Caspian Basin occurred in the early to middle Miocene (Krhostvy et al., 1993; Jones & Simmons, 1996). This is expressed by occurrences of chocolate brown argillites and brownish carbonate argil-
lites that are intercalated with sandstone and limestone beds of yellowish-brown colour, deposited in a lacustrine or restricted shelf set-
ting (Popov et al., 2008).
Studies of Maikopian strata in eastern Azer-
bajian did not yield a consistent timing of depo-
sition, because index fossils are absent and other faunal elements are either scarce or poorly preserved in most beds (Hudson et al., 2008; Bechtel et al., 2014). However, based on biostratigraphic indications and chemomo-
graphic correlations between different outcrops (Boyanata, Göytepe, Perikişkil, etc.), Hudson et al. (2008) and Popov et al. (2008) have assigned the lowermost part of the Islam Dağ section to the late Oligocene, while the middle and upper parts have been dated to the early Miocene. Very recently, Washburn et al. (2018) have revisited the stratigraphy of the Islam Dağ section and have re-assigned the recently exposed middle part to the early Miocene and the upper part to the middle Miocene, respec-
tively, based on Re–Os geochronology.
Little is known about the burial history of this offshore sedimentary succession, but it is likely that rapid subsidence and burial have occurred since the late Miocene (Devlin et al., 1999), followed by fast uplifting of the Cenozoic strata during the development of the Greater Caucasus (Forte et al., 2015). From Rock-Eval pyrolysis data (i.e. <435°C T_max; a maturity indicator recording the temperature at which the maxi-
mum S2 peak is achieved during pyrolysis) it is evident that the Miocene rocks are thermally immature and thus a maximum burial tempera-
ture slightly below or close to the early oil win-
dow (ca <80°C) can be inferred (Hudson et al., 2016).

MATERIAL AND ANALYTICAL METHODS

Field work, samples and sample preparation
Geological mapping of the Islam Dağ section was carried out during several field campaigns from April to May 2018, where the outcrops were logged and studied bed by bed at a resolution of ca 5 cm. The mostly fine laminated argil-
lites were categorized using the classification of Fuchtbauer (1988). The main types of limestone microfacies were classified using the scheme of Tucker & Wright (1990). Hand-size specimens (37 in total) were collected from the Islam Dağ section (Fig. 2) for petrographic, mineralogical and chemical characterization. A 20 to 30 cm thick surface layer was removed prior to sam-
pling to avoid oxidized samples. Moreover, the collection of samples containing siltstone lenses, limestone intercalations and gypsum nodules has been avoided to ensure comparison between sedimentary facies and geochemical proxies recorded in the argillites. For correlation of the sedimentary units the stratigraphy of Washburn et al. (2018) has been applied.
For the separation of the clay mineral fraction, six bulk samples (taken at 5-6 m, 24.5 m, 47.3 m, 56.3 m, 61.6 m and 81.4 m in the Islam Dağ section) were treated with 10% acetic acid for 1 h to dissolve carbonates, if present. Then, the acid-insoluble fraction was dispersed in an ultrasonic bath for 10 min. Subsequent to Atter-
berg sedimentation the <2 μm size fraction was collected, following separation by 0.45 μm cellul-
lose acetate membrane (Sartorius) filters using a suction filtration unit and drying at 40°C.

X-ray diffraction
X-ray diffraction (XRD) patterns were collected for mineral identification and quantification on
The XRD patterns were measured using a PANalytical X’Pert PRO diffractometer operated at 40 kV and 40 mA (Co–Kα radiation) and equipped with a high-speed Scientific X’Celerator detector (Malvern PANalytical, Malvern, UK), 0.5° antiscattering and divergence slits, primary and secondary soller and spinner stage. Bulk samples were mixed with 20 wt.% zincite (ZnO) as an internal standard and ground in a McCrone micronizing mill (The McCrone Group, Westmount, IL, USA) for 8 min. Random preparations were then made using the front loading technique and examined from 4 to 85° 2θ with a step size of 0.008° 2θ and a count time of 40 sec:step⁻¹. Mineral quantification was carried out by Rietveld analysis of the XRD patterns using the PANalytical X’Pert HighScore Plus Software and a pdf-4 database. The accuracy of the XRD results was verified by comparison with mass-balance calculations based on chemical compositions of bulk samples (see section on X-ray fluorescence). Assuming idealized compositions for quartz, feldspar (K-feldspar and albite/plagioclase), illite, kaolinite, chlorite (Mg-chlorite), nontronite (Fe-smectite), zeolite (K-clinoptilolite), gypsum, jarosite, pyrite, calcite, anatase and the amorphous phase (organic matter), the deviation of XRD and chemical data was ≤3 wt. %.

Fig. 1. (A) Location of Azerbaijan in Western Asia. (B) Detailed location map of the Islam Dağ section, located in the Gobustan–Absheron depression in eastern Azerbaijan (modified after Hudson et al., 2008). Inset map shows relative location in Azerbaijan.
For further XRD analysis of the clay mineral (<2 μm) fraction, oriented preparations were made using the procedure described in Baldermann et al. (2014). Briefly, ca 50 mg of sample was mixed with 5 ml of ultrapure water (Millipore Integral 3: 18.2 MΩ·cm⁻¹; MilliporeSigma, Burlington, MA, USA) and dispersed ultrasonically for 10 min, following suction of the clay in suspension through a ceramic plate of ca 4 cm². The clay films were analyzed from 3 to 30° 2θ with a step size of 0.02° 2θ and a count time of 2 sec·step⁻¹ each at air-dried states, after solvation with ethylene glycol (EG) and after heating to 550°C for 1 h. The XRD patterns were recorded on a Philips PW 1830 diffractometer (Cu-Kα: 40 kV, 30 mA; Philips, Amsterdam, The Netherlands) and outfitted with automatic slits, a graphite monochromator and a scintillation counter. The illite crystallinity and the Esquevin index were derived from these XRD patterns in order to track changes in the evolution of the detrital flux within the studied interval (Bout-...
The illite crystallinity (in °2θ) refers to the full width at half maximum (FWHM) measured on the d001-reflection (ca 10 Å) of illite at EG-solvated states (Chamley, 1989). This parameter is a measure for the metamorphic degree and temperature in pelitic rocks, i.e. a low illite crystallinity reflects a high metamorphic facies. The Esquevin index (which is referred to as illite chemistry index) is defined by the intensity ratio of the illite peaks measured at 5 Å and at 10 Å (Esquevin, 1969). This ratio and can be used as a chemical weathering index.

X-ray fluorescence

The chemical composition of bulk rock samples was analyzed using a PANalytical PW2404 wavelength dispersive x-ray fluorescence (XRF) spectrometer (Malvern PANalytical). Powdered samples (ca 2-0 g) were heated to 950°C for 1 h to remove volatiles (for example, H2O and CO2) and then the loss on ignition (LOI) was determined by gravimetric analysis. Subsequently, 1.0 g of material (dried at 105°C) was fused at ca 1200°C in a fully-automatic PANalytical Peri’X 3 bead preparation system using 6.0 g of Li2B4O7 as fluent agent (Malvern PANalytical). The fusion time was reduced to <3 min in order to avoid volatilization and loss of S. The tablets were analyzed together with a range of United States Geological Survey (USGS) standards. The analytical error is ±0.5 wt. % for the major elements.

For the determination of distinctive provenance signals discriminant function analysis of major elements data was carried out with the SPSS package, following the manual of Roser & Korsch (1988). The MnO and P2O5 were not considered in the analysis, because their concentrations are low and the analytical precision worse than for the major elements. For palaeo-climate reconstructions the chemical index of alteration (CIA) can be used (Nesbitt & Young, 1982), which expresses the molar volumes of [Al2O3/ (Al2O3 + Na2O + K2O + CaO*-) ]×100. This weathering proxy is based on the progressive transformation of unstable minerals, like alkali feldspar, to more stable clay minerals under ambient environmental conditions, and can be quantitatively traced by following changes in the ratio of immobile Al2O3 to the mobile cations (K+, Na+ and Ca2+), expressed as oxides (Richoz et al., 2017). Calcium oxide present as carbonate and/or gypsum was subtracted from the total CaO content (on the basis of XRD data) to obtain CaO* of the silicate fraction. The CaO present as phosphate was not considered in the calculation, because it increases the CIA value by less than two units if all P2O5 is assigned to apatite. Detrital indicator ratios (K/Al, Ti/Al, etc.), C–S–Fe distributions and Fe/Al ratios were calculated to constrain the detrital input flux, to track changes in the intensity and pathways of weathering in the source rock areas and to trace early diagenetic processes (e.g. Johnson et al., 2010).

Total organic carbon

The total organic carbon (TOC) content was determined on powdered samples (37 in total) following catalytic combustion and analyses of the originated CO2 by non-dispersive infrared detection using a Shimadzu TOC-VcPH+ASI-V analyzer (Shimadzu Corporation, Kyoto, Japan). The analytical error of TOC analyses is ±5%, as determined by replicate measurements of sodium salicylate (C7H5NaO3), sodium carbonate (Na2CO3) and D-(+)-glucose (C6H12O6) standards (all p.a. quality, from Roth; Carl Roth GmbH + Co. KG, Karlsruhe, Germany).

Scanning electron microscopy

The mineralogical composition, the particle form and the particle shape of authigenic and detrital (clay) mineral phases were studied by scanning electron microscopy (SEM) using a JEOL JSM-6610LV microscope (JEOL Limited, Tokyo, Japan) operated at an accelerating voltage of 20 kV (Institute of Geology and Geophysics, Azerbaijan National Academy of Science). The microscope is equipped with a low vacuum secondary electron (SE) detector and an Oxford Instruments silicon drift detector for energy-dispersive X-ray spectrometry (EDS) analysis (Oxford Instruments, Abingdon, UK). Rock chips were therefore prepared on standard SEM stubs and sputter coated with carbon to reduce charging.

Stable isotopes

The oxygen and carbon isotopic composition of carbonates was measured using a ThermoFisher Scientific Gasbench II connected to a ThermoFinnigan DELTA plus XP mass spectrometer (Thermo Fisher Scientific, Waltham, MA, USA) at the stable isotope laboratory of the JR-AquaConSol GmbH (Graz, Austria). Samples...
were prepared following the procedure described in Dietzel et al. (2009). Briefly, concentrated phosphoric acid was injected into the individual sample vials containing 300 to 600 µg of sample and reacted with the carbonates for 2 h at 70°C prior to the continuous-flow isotopic ratio mass spectrometric analyses. The measured oxygen and carbon stable isotope values are reported in terms of delta notation (for example, δ²⁰⁸O and δ¹³C) relative to the Vienna Pee Dee Belemnite (VPDB) standard. The analytical precision is ±0.1‰ for δ¹³C and ±0.08‰ for δ²⁰⁸O, respectively.

RESULTS

Sediment petrography and bulk mineralogy of the Islam Dağ section

The combination of field work and sedimentological–mineralogical analyses of the bulk samples is given in Table S1. This provides a logical–mineralogical analyses of the bulk sample. The current microscopic study, however, reveals trace amounts of rhombohedral low-Mg calcite spar (LMC), about 5 µm in largest dimension, infilling former pore space of these rocks, which is typical for neomorphic calcite spar. With the naked eye, the argillites do not show distinctive signs of oxidation. These rocks have been deposited in the early Miocene, applying the stratigraphy of Washburn et al. (2018).

Unit 2: Light grey argillites
Massive and ‘carbonate-free’ argillites of light grey to greyish-black colour are exposed between ca 31.5 m and 73.5 m in the profile (Fig. 2A and C). Macroscopically oxidized samples from this unit are characterized by large occurrences of patches of rhombohedral jarosite crystals of yellowish-green colour on the sample surfaces (Fig. 4B). Unaltered samples consist dominantly of quartz (16 to 35 wt. %), feldspar (12 to 22 wt. %), illite (31 to 40 wt. %) and organic matter (8 to 13 wt. %). Minor amounts belong to smectite (3 to 9 wt. %), kaolinite (1 to 8 wt. %), chlorite, zeolite and jarosite (each 0 to 3 wt. %) as well as anatase and pyrite (<1 wt. %) (Fig. 3). Rhombohedral to rounded LMC spar, ca 2 to 5 µm in size, is rarely present in these rocks. In contrast to the argillites from unit 1, these rocks do not contain siderite concretions. A single volcanic ash layer crops out at ca 47.1 m in the profile. The transition between the early Miocene and the middle Miocene is located near the top of this unit (Washburn et al., 2018), although the precise stratigraphic boundary could not be resolved.

Unit 3: Chocolate brown argillites with mudstone beds
Massive argillites of light chocolate brown to greyish-brown colour are exposed between ca 73.5 m and 108 m in the profile (Fig. 2A and D). The argillites are traversed by thin lamellar beds (ca 1 to 2 cm) and nodules of gypsum. Polygonal desiccation cracks, dissolution breccia and tepee structures can be found in this interval. The argillites consist of quartz (17 to 22 wt. %), feldspar (17 to 21 wt. %), illite (34 to 39 wt. %) and organic matter (7 to 12 wt. %). Kaolinite, smectite (each 4 to 6 wt. %), platelet-prismatic gypsum (0 to 5 wt. %), rhombohedral to rounded LMC (0 to 4 wt. %), zeolite and anatase (1 to 3 wt. % in total) represent minor constituents (Figs 3 and 4C). In the upper part of this unit marly mudstone beds, about 0.1 to 0.5 m thick, of yellowish-beige colour crop out. These rocks comprise high amounts of LMC (>90 wt. %), besides quartz and clay minerals, and show a sharp erosional contact to the
surrounding ‘low-carbonate’ argillites. However, these rocks still contain trace amounts of rhombohedral LMC spar, ca 5 \( \mu \)m in size. Sandstone beds were not found in this unit, contrasting prior results of Popov et al. (2008). This section has been deposited in the early middle Miocene (Washburn et al., 2018).

**Unit 4: Carbonate argillites with mudstone beds**

The top of the Islam Dağ section is dominated by structureless carbonate-bearing argillites of light-grey to greyish-brown colour and massive mudstone beds (ca 0.2 to 0.4 m thick) of yellowish to beige colour, deposited in the alternate

---

© 2019 The Authors Sedimentology published by John Wiley & Sons Ltd on behalf of International Association of Sedimentologists, *Sedimentology*, 67, 152–172
mode (ca 108 to 145 m in the profile; Fig. 2A). The argillites consist mainly of quartz (15 to 21 wt. %), feldspar (13 to 20 wt. %), illite (27 to 37 wt. %), LMC (2 to 12 wt. %), high-Mg calcite (HMC; up to 19 wt. %) and organic matter (8 to 11 wt. %), in addition to kaolinite and smectite (each 3 to 5 wt. %); jarosite, anatase and zeolite (each <1 wt. %) (Fig. 3). Both LMC (ca 3 mol % MgCO₃) and HMC (ca 9 mol % MgCO₃) have a rounded to rhombohedral crystal shape, a spartic appearance and a crystal size between 1 µm and 5 µm (Fig. 4D). The mudstones comprise LMC (78 to 91 wt. %), quartz (4 to 7 wt. %), clay minerals (5 to 8 wt. % of illite, chlorite and kaolinite) and dolomite (1 to 3 wt. %; very seldom). This sequence has been deposited in the middle Miocene, according to Washburn et al. (2018).

Clay mineralogy of the Islam Dağ section

Four types of clay minerals were identified based on the XRD study of the <2 µm size fraction (Fig. 5) and bulk fraction, namely illite, chlorite, kaolinite and ferruginous smectite.

Illite displays sharp reflections at 9.94 Å (d₀₀₁), 4.99 Å (d₀₀₂) and 3.34 Å (d₀₀₃) and contains ca 98% illite layers and ca 2% smectite layers (Fig. 5), as calculated from the relationship between the position of d₀₀₂ peak after EG-solvation and the percentage of illite layers in mixed-layered illite–smectite (Baldermann et al., 2013, 2017). Polytype diagnostic reflections reveal a 2M₁ polytype, which is common for detrital illite in marine sediments. Measurements of the illite crystallinity and of the Esquévin index yielded values between 0.4 to 0.5° and from 0.3 to 0.4, respectively, independent of the stratigraphic position of the samples.

In the bulk samples, chlorite (i.e. clinochlore) was identified based on sharp reflections at 14.23 Å (d₀₀₁), 7.08 Å (d₀₀₂), 4.74 Å (d₀₀₃) and 3.52 Å (d₀₀₄). The absence of chlorite in the <2 µm size fraction (Fig. 5) and the relatively low burial temperature (for example, <80°C) point to a detrital nature of this mineral phase.

Poorly crystallized kaolinite shows broad reflections at 7.15 Å (d₀₀₁) and 3.57 Å (d₀₀₂) (Fig. 5), which disappeared after heat treatment due to dehydroxylation. The SEM results reveal neither an association of kaolinite with altered feldspar nor a vermiform structure of kaolinite aggregates (Fig. 4), implying a detrital origin of this phase. However, kaolinization of alkali feldspar cannot be fully ruled out, meaning that a fraction of kaolinite could be diagenetic in origin.

Smectite displays a broad d₀₀₁-reflection at ca 12.6 Å at air dried states, which indicates that Na⁺ ions mainly occupy the interlayer space. After EG-solvation and subsequent to heating the basal spacing changed to ca 17-1 Å and ca 10-0 Å, respectively, which is typical for smectite (Fig. 5). The diagnostic d₀₆₀-reflection was at

![Fig. 5. X-ray diffraction (XRD) patterns of oriented clay preparations (<2 µm) from the Islam Dağ section (for example, IDB 06: 5-6 m, IDB 26: 24-5 m, IDB 55: 47-3 m, IDB 65: 56-3 m, IDB 72: 61-6 m and IDC 40: 81-4 m in the running profile in Fig. 2), collected after EG-solvation. Samples are not presented in stratigraphic order for better visualization. Mineral abbreviations: smectite (Smc), illite (Ilt), kaolinite (Kln) and quartz (Qz). c.p.s. = counts per second.](image-url)
1.51 Å, reflecting the dioctahedral nature of this mineral phase and the presence of sufficient amounts of structural Fe(III) (Baldermann et al., 2017; Voigt et al., 2018). The flaky to veil-like particle form (Fig. 4A and C) of ferruginous smectite and its association with zeolite minerals and volcanic ash layers imply a diagenetic origin.

Changes in the clay mineral assemblages across the entire Islam Dağ section are shown by the illite+chlorite–kaolinite–smectite ternary diagrams (Fig. 6). Illite is the dominant component (64 to 87%) of the clay mineral fraction with an average of 78%. Smectite (7 to 20%) and kaolinite (3 to 15%) are present in lesser abundance with a similar average content of 10 to 11% throughout in the profile. Chlorite (0 to 7%) is scarce in units 1 and 2 with an average content of 1%, and it disappears in units 3 and 4. Apart from the observed relatively homogenous distribution of the clay mineral assemblage across the Islam Dağ section (Fig. 6), some distinctive trends can be recognized when considering the individual proportion of each clay minerals among the total clay mineral fraction over the stratigraphic profile (Table S2). Smectite and kaolinite generally show a similar trend, which is opposed to that of illite, i.e. they progressively increase in unit 1 reaching the highest values in unit 2, subsequently show a sudden drop at the base of unit 3 and then stay comparably low in unit 4.

**Major and minor element composition of the Islam Dağ section**

The major and minor elemental composition of the argillaceous rocks from the Islam Dağ section is highly variable (Table S3) due to changes in lithology and grain-size variations. Accordingly, SiO₂ (39.2 to 62.4 wt. %), Al₂O₃ (11.8 to 23.4 wt. %), Na₂O (0.6 to 2.2 wt. %), K₂O (1.7 to 2.9 wt. %) and CaO (0.1 to 14.3 wt. %) contents are directly attributable to varying abundances of quartz, feldspar, illite, calcite and minor kaolinite and zeolite, complying with the mineralogical results (Fig. 3). The MgO (1.4 to 3.8 wt. %), Fe₂O₃ (2.4 to 9.8 wt. %), SO₃ (0.01 to 2.4 wt. %) and TiO₂ contents (0.4 to 0.9 wt. %) mostly reflect variations in minor amounts of smectite, chlorite, pyrite, jarosite, gypsum and anatase, while the LOI (11.1 to 23.0 wt. %) contents belong mainly to organic matter, phyllosilicates and carbonates. The MnO, P₂O₅, ZrO₂ and SrO (0.01 to 0.2 wt. %) occur in low amounts and reflect trace mineral impurities. The concentrations of redox-sensitive trace metals (for example, Cr, Co, V, Ni, Mo, Th and U) were always below the detection limit of the XRF analyses (ca 0.01 wt. %) and hence cannot be used for the interpretation of palaeo-redox conditions.

The CIA values (left part of Fig. 7A) range between 75.5 and 89.1 (CIA; 81.9 ± 4.2, on average) and plot well around the fields of illite and smectite (75 to 90), which reflects intense weathering rates, according to McLennan et al. (1993), and/or recycling of clayey sediments in the basin. These high CIA values correspond to high proportions of clay minerals (especially illite) in the argillaceous rocks and suggest that the fine-grained material is derived from chemical weathering of endogenous or metamorphosed host rocks, considering that fresh basalt, granite/graywacke and feldspar have CIA values of 30 to 45, 45 to 55 and 50, respectively (Nesbitt & Young, 1984). Plotting the XRF data in the A–CN–K (Al₂O₃ – CaO* + Na₂O – K₂O) diagram (Fig. 7A) reveals that most samples plot slightly above the compositional ranges of the Post-Archean Australian Shale (PAAS) and Average Proterozoic Shale (APS) or follow predicted weathering trends for Upper Continental Crust (UCC) rocks. Given that kaolinization of alkali feldspar was not observed, it can be
inferred that the argillites were affected by sorting, as seen in the slight shift towards the A pole of the diagram. Variations in the tectonic setting and/or burial diagenetic illitization of smectite have played only a minor role. Accordingly, the plot of the chemical data in the A-CNK-FM (Al₂O₃ – CaO* + Na₂O + K₂O – Fe₂O₃ + MgO) diagram (Fig. 7B) shows a mixed composition, which is typical for heterogeneous, clayey sediments that are subjected to a certain degree of intra-basin recycling (McLennan et al., 1993).

**Total organic carbon and amorphous phase contents**

The TOC content varied from 1.8 to 6.4 wt. %. No systematic trend in TOC was recognized in the profile, although two different types of samples can be distinguished: (i) samples with a low TOC content (1.8 to 2.3 wt. %; n = 5); and (ii) samples with a moderate to high TOC content (3.2 to 6.4 wt. %; n = 32). The low TOC values coincide with samples having low pyrite contents (<1 wt. %), but high jarosite contents (up to 3 wt. %), which suggests that these samples could have suffered from post-depositional oxidation. The high amorphous phase content of these oxidized samples may be due to ‘contamination’ by glassy components from adjacent volcanic ash layers.

The TOC values obtained for the non-oxidized samples show a positive linear correlation with the amorphous phase content determined by XRD ($R = 0.69, n = 32$). The slope of 2.03 of the best-fitting function is close to the empirical (1.9) and theoretical (2.0) factors frequently used for converting soil organic carbon to soil organic matter (Pribyl, 2010). This relationship implies that other amorphous phases (volcanic ash, silicifying organisms, etc.) are negligible and that the amorphous phase content is about equivalent to the organic matter content.

**Oxygen and carbon isotopic composition of carbonates from the Islam Dağ section**

The rhombohedral LMC spar from the lower part of the Islam Dağ section (units 1 and 2) displays a high variation in the $\delta^{13}C$ and $\delta^{18}O$ values in the range from $-34.5$ to $-17.3\%_{\text{VPDB}}$ for $\delta^{13}C$ and from $-34.7$ to $-12.5\%_{\text{VPDB}}$ for $\delta^{18}O$ (Fig. 8; Table S3). A slightly lower scatter in the values of $\delta^{13}C$ ($-17.3$ to $+1.7\%_{\text{VPDB}}$) and $\delta^{18}O$ ($-17.6$ to $-4.8\%_{\text{VPDB}}$) is evident for the neomorphic LMC and HMC spar, and their admixtures, exposed in the upper part of the profile (units 3 and 4; Fig. 8), although petrographically these authigenic carbonates do not differ much from the lower units.

**DISCUSSION**

**Post-depositional alteration**

The argillites from the Islam Dağ section show unequivocal evidence for post-depositional alteration, such as oxidation of pyrite and formation of jarosite as well as alteration of volcanic ash and precipitation of ferruginous smectite and zeolite. An influence of meteoric diagenesis is indicated by the occurrences of neomorphic LMC (and HMC) spar throughout in the profile. Some samples showing low TOC contents have suffered from post-depositional oxidation. These samples were not considered in the further discussion. In contrast, neither signs of pedogenesis, such as formation of calcrete, caliche and soil clays, nor smectite-illitization were found, which suggests that long periods of subaerial exposure and burial diagenetic processes did not modify the original petrographic, mineralogical and chemical signatures of the argillites (Mackenzie, 2005; Richoz et al., 2017; Hellwig et al., 2018). Cementation and compaction by late diagenesis did not play a role taking the low burial temperatures (ca 50 to 80°C) these offshore Miocene deposits have seen (Hudson et al., 2016). The latter features are an important pre-requisite for the interpretation of depositional environments and for the reconstruction of palaeo-climate based on chemical proxies and weathering indices.

**Early diagenetic processes and sub-recent oxidation**

Microbial reduction of labile Fe-oxyhydroxides coupled with microbial heterotrophic and abiotic sulphate reduction soon after sediment deposition (Raiswell & Canfield, 2012) could have provided a secondary pool of dissolved Fe$^{2+}$ and S$^-\text{ ions}$ that are required for the formation of pyrite (Figs 3 and 4A). Under such reducing conditions, degradation of organic matter is less efficient compared to oxidizing conditions, explaining the high TOC contents of the argillites from unit 1 (4.9 ± 0.6 wt. %). This coincides with the observed low degree of alteration of sediments from unit 1, judging from visual inspection of the outcrop. In contrast, the
argillites from unit 2 show distinct signs of oxidation, such as occurrences of patches of jarosite on the rock’s surface (Figs 2 and 3) and partly reduced TOC contents (ca ≤ 2 wt. % in Table S3). It is possible that jarosite has been formed by the microbial mediated oxidation of pyrite under low pH conditions (for example, pH < 4) and at ambient temperature (e.g. Parafiniuk et al., 2016; Lewis et al., 2018). The irregular to patchy appearance of the rhombohedral jarosite crystals may support this hypothesis (Figs 3 and 4B). The in situ conversion of pyrite into jarosite during marine diagenesis is unlikely, given the high solubility of Na/K- or hydronium-jarosite in aqueous environments ($K_{sp} = 10^{-14.8}$ to $10^{-7.1}$ at 25°C). The absence of oxidation products of pyrite, such as goethite and hematite, and the overall high TOC contents (4.9 ± 0.8 wt. %) of argillites from unit 2 support this assertion (Baron & Palmer, 1996; Kotler et al., 2008). For the same reasons, the formation of gypsum through alteration of pyrite seems implausible. Indeed, desiccation cracks, dissolution breccia and tepee structures associated with

---

**Fig. 7.** Chemical compositions of argillaceous rocks from the Islam Dağ section plotted in the A–CN–K ($\text{Al}_2\text{O}_3$ – $\text{CaO}^* + \text{Na}_2\text{O} – \text{K}_2\text{O}$) diagram (A) and in the A–CNK–FM ($\text{Al}_2\text{O}_3$ – $\text{CaO}^* + \text{Na}_2\text{O} + \text{K}_2\text{O} – \text{Fe}_2\text{O}_3 + \text{MgO}$) diagram (B). The compositions of Upper Continental Crust (UCC), Average Proterozoic Shale (APS), Post-Archean Australian Shale (PAAS) and of some index minerals are included for comparison. The average chemical index of alteration (CIA) value is indicated in the left part of the A–CN–K diagram (A < 50 is not shown).

© 2019 The Authors Sedimentology published by John Wiley & Sons Ltd on behalf of International Association of Sedimentologists, *Sedimentology*, 67, 152–172
the gypsiferous argillites from unit 3 suggest that gypsum is primary. Considering the sedimentary structures mentioned before and occurrences of subhedral to rhombohedral HMC in the subsequently deposited carbonate-bearing argillites from unit 4, it seems likely that the gypsum nodules and the neomorphic HMC spar have been precipitated from seawater-derived pore solutions under evaporitic conditions (Mackenzie, 2005; Swart, 2015; Mavromatis et al., 2017).

The high TOC contents of units 2 and 4 (51/C1<12/C61/C1 wt. % and 4<12/C61/C1 wt. %, respectively) indicate that post-depositional alteration due to oxidation is negligible.

Occurrences of ferruginous smectite and zeolite minerals throughout the Islam Dağ section (Fig. 3) are likely related to alteration of volcanic ash layers, although a minor contribution from detrital sources cannot be fully ruled out. Authigenic smectite can be differentiated from the detrital clay minerals by the deviant particle morphology and the smaller grain size. Ferruginous smectite particles have a flaky to veil-like form and are <1 μm in largest dimension (Fig. 4A and C). Detrital clay minerals are generally larger in size (ca >1 to 5 μm) and have a platelet, platy or rounded particle form (Fig. 4B). The close association of volcanic ash layers, ferruginous smectite having Na+ ions in the interlayer sites and K/Na-clinoptilolite, especially in units 1 and 2 (Figs 3 and 5), suggests their formation during early marine diagenesis at low temperature (Lawrence et al., 1979; Abdullayev & Leroy, 2016).

**Meteoric diagenesis and carbonate formation**

Two types of authigenic carbonate minerals have been identified in the Islam Dağ section: LMC (ca 4 mol % MgCO3) and HMC (ca 9 mol % MgCO3). The LMC occurs in trace amounts (ca <0.5 wt. %) between 0 m and 87 m in the profile, becoming more enriched towards the top of the section, while HMC only occurs in the uppermost samples of unit 4 (Fig. 3). The characteristic δ13C and δ18O values (Fig. 8) and the spatial distribution of LMC and HMC in the profile suggest a different origin of these carbonates.

Low magnesium calcite is strongly depleted in 13C and in 18O with respect to common marine carbonates (Veizer, 1983). Such extreme 12C
enrichments are frequently related to oxidation of methane, liberated from decaying organic matter, followed by the conversion of methane into dissolved carbonate species (DIC) and subsequent precipitation of isotopically light carbonates. Such negative $\delta^{13}C$ values have been reported for the methane-derived carbonates ($-46.8$ to $-41.5\%$ VPDB) from the native sulphur deposit at Machów (south-east Poland) and for the cold seep carbonate deposits ($-40.2$ to $-0.1\%$ VPDB) from Marmorito (Italy) (Böttcher & Parafiniuk, 1997; Peckmann et al., 1999). In this line, Johnson et al. (2010) have shown the bulk organic matter from the Islam Dağ section to be isotopically light ($-18$ to $-30\%$ VPDB for $\delta^{13}C_{\text{org}}$), suggesting that its oxidation could have provided the source of carbon for LMC precipitation. However, the $\delta^{18}O$ isotope signatures of such methane-derived carbonates are completely different ($-7$ to $+5\%$ VPDB), compared to LMC from the Islam Dağ section (up to $-35\%$ VPDB), implying more complex formation processes. Considering the $\delta^{18}O$ isotopic composition of the present-day Kura and Samur rivers and of local groundwater from Baku ($ca$ $-10.2$ to $-9.6\%$ SMOW – standard mean ocean water) (Lavrushin et al., 2015; Nadiri et al., 2018), it is clear that LMC should have been precipitated under the influence of meteoric waters depleted in $^{18}O$ (Beck et al., 2005; Dietzel et al., 2009; Peryt et al., 2012; Boch et al., 2018). It is proposed that recent sub-surface precipitation of jarosite may have acted as a mineral sink for $^{18}O$, i.e., isotopic equilibrium between the meteoric solution and dissolved $\text{SO}_4^{2-}$ (from weathering of pyrite) could have been approached, producing meteoric solutions enriched in $^{16}O$. The interaction of fluids heavily depleted in $^{18}O$ with isotopically light methane at ambient temperature could produce DIC signatures that are suitable for the formation of LMC enriched in $^{18}O$ and $^{12}C$.

High magnesium calcite is thought to have been formed during early marine diagenesis at elevated Mg/Ca ratios of the pore water (Tucker & Wright, 1990; Swart, 2015; Mavromatis et al., 2017; Purgstaller et al., 2017); thus recording isotopic signatures ($ca$ $\pm 5\%$ VPDB for $\delta^{13}C$ and $\delta^{18}O$; Fig. 8) similar to other marine Miocene carbonate deposits, like the middle Miocene lacustrine carbonates from the Bannockburn Formation at Vinegar Hill in New Zealand (Horton et al., 2016) and the bryozoan-rich sediments from the early to middle Miocene Central Paratethys (Key et al., 2013). Assuming a $\delta^{18}O$ isotopic composition of Miocene seawater of $-1\%$ SMOW, HMC has been formed at $ca$ $35 \pm 2^\circ C$, using the equations of Epstein et al. (1953) and Craig (1965) modified by Anderson & Arthur (1983). This temperature estimate is higher than reported for the time-equivalent deposits of the Central Paratethys (for example, $12$ to $21^\circ C$), but similar to modern and ancient carbonates formed in evaporative, lacustrine and restricted shelf environments (Veizer, 1983; Tucker & Wright, 1990; Baldermann et al., 2012, 2015b; Swart, 2015). In essence, the $\delta^{13}C$ and $\delta^{18}O$ isotopic signals of authigenic carbonates from the Islam Dağ section are not particularly useful for stratigraphic correlations and for palaeo-environmental studies, in contrast to chemical proxies and weathering indices based on the siliciclastic fraction.

**Provenance of sediments**

Discriminant function analysis of major elements indicates generally a mixed provenance of the Miocene argillaceous rocks from Islam Dağ section (Fig. 9). The majority of the samples plot in the ‘quartz sedimentary provenance’ field and few fall into the ‘mafic igneous provenance’ group (Roser & Korsch, 1988). No distinct difference in the provenance was observed between the four sedimentary units, which suggests a rather constant detrital input of siliciclastic material during the Miocene and no significant changes in the source area(s).

The current study infers that the Russian Platform was the main source area for the argillaceous rocks from the Islam Dağ section at this time, because this area is represented mainly by Precambrian gneiss, amphibolite, conglomerate and sandstone, Cambrian sandstones with clay lenses, Palaeozoic schist, and carbonate and Mesozoic sandstone and shale deposits (Mammadov & Karimov, 1987; Buryakovsky et al., 2001). Physical weathering of these potential host rocks coupled with long transportation distances and intra-basin reworking action will produce mixed, fine-grained sediments rich in detrital components, similar to those of the Islam Dağ section (Figs 4 and 7B). If considering that there was no important illite diagenesis, the measured illite chemistry index (0.3 to 0.4) and illite crystallinity (0.4 to 0.5° 2θ) may support this assertion: an illite chemistry index lower than 0.5 represents Fe-rich and Mg-rich illites, which are formed during physical erosion and weak chemical weathering (Esquevin, 1969).
whereas a high illite crystallinity index and corresponding low Küber indices (see Table S2) are indicative of a provenance from low-grade metamorphosed domains (Bout-Roumazeilles et al., 2013), in agreement with regional geology and observed trends of terrestrial input fluxes, based on δ13Corg isotopes and hydrogen indices (Hudson et al., 2008). In this line, Popov et al. (2004) have argued that the major positive topographic features, including the Russian and Pre-Ural Highlands, the Ural Mountains and the Ukrainian and Donets lands, drained by the Palaeo-Volga, Palaeo-Don and Palaeo-Donets, could have acted as provenance areas for the sediments of the Eastern Paratethys basins during the early to middle Miocene. Apart from that, a minor contribution of volcanogenic detritus and sporadic input of basaltic–intermediate material from the Greater Caucasus Mountains, for example, from the early Jurassic diabase and gabbro–diabase complex, is indicated by this study’s data (Fig. 9). The latter supports the hypothesis that the Greater Caucasus Mountains were emerging during deposition of the Maikop facies and the Spiralisian Formation in the late Oligocene and early Miocene, although major uplifting probably did not occur before the middle Miocene (e.g. Ershov et al., 2003; Vincent et al., 2007; Johnson et al., 2010).

Weathering trends and palaeo-climate

Geochemical proxies and clay mineral assemblages are commonly used for palaeo-environmental analyses of argillaceous rocks (McLennan et al., 1993; Pearce et al., 2005; Chen et al., 2013; Hofer et al., 2013; Sachsenhofer et al., 2015; Richoz et al., 2017; Hellwig et al., 2018). Specifically, major and minor elemental compositions of argillites and clay mineral distributions often record the dominant weathering processes and paths in the source areas driven by palaeo-climate. Physical weathering dominates under arid (or cold) climate conditions and results in the mechanical breakdown of parent rocks and minerals without significant mineralogical and chemical alteration. Chemical weathering is enhanced under humid climatic conditions, leading to distinct changes in the chemical and mineralogical composition of the sediments, as mobile cations (K+, Na+, Ca2+, etc.) are preferentially leached away during this process, leaving immobile elements (Al, Si, etc.) in the residue (Nesbitt & Young, 1982). Considering the major input of sediments from the Russian Platform in the early to middle Miocene, as shown before, changes in weathering indices, detrital indicators and clay mineral distributions throughout the Islam Dağ section should reflect variations in

Fig. 9. Discrimination plot of discriminant functions 1 and 2 showing a mixed provenance of the argillaceous rocks from the Islam Dağ section. The four main provenance groups, P1-mafic, P2-intermediate, P3-felsic and P4-quartzose, are included for comparison (Roser & Korsch, 1988).
palaeo-climate in the hinterland. In the present study, the detrital indicators show a co-variation with one another (for example, Na/Al, K/Al, Si/Al and Ti/Al ratios) and with the percentage of illite (i.e. the most abundant mineral in the clay fraction, see Table S2), and accordingly a clear anti-correlation with the CIA values (Fig. 10). Thus, shifts in these parameters across the Islam Dağ section can be used to track changes in palaeo-climate and in the intensity of chemical weathering in the source areas during the early to middle Miocene. In detail, comparatively low CIA values (82 ± 2), high ratios of Na/Al (0·10 ± 0·03), K/Al (0·23 ± 0·02), Si/Al (2·67 ± 0·17) and Ti/Al (0·04 ± 0·01), and high amounts of illite in the clay mineral fraction are seen for the argillites from unit 1, which could be attributed to less intensified chemical weathering under arid conditions during the early Miocene (Hofer et al., 2013). At the boundary between units 1 and 2, an abrupt shift to comparatively higher CIA values and lower ratios of Na/Al, K/Al, Si/Al and Ti/Al can be seen, probably reflecting an increase in humidity in the mid-early Miocene and intensified chemical weathering (Fig. 10). The gradual increase of the contents of kaolinite – a typical weathering product of feldspar (Singer, 1980, 1984) – and smectite, if detrital, in this interval (Fig. 3; Table S2) may corroborate this assertion. A ‘long-term’ transition towards comparatively lower CIA values, higher element/Al ratios and increasing proportions of illite in the clay mineral fraction is observable between units 2 and 3, which may be related to an aridification trend and related reduced rates of chemical weathering during the mid-early Miocene to early middle Miocene (Fig. 10). Physical erosion and reduced chemical weathering under semi-arid to arid conditions could have prevailed during the middle Miocene, as indicated by comparatively low CIA values (76 ± 1), high Na/Al (0·18 ± 0·02), K/Al (0·26 ± 0·02), Si/Al (3·07 ± 0·12) and Ti/Al (0·04 ± 0·01) ratios as well as the highest illite contents (see Fig. 10; Table S2). These spatiotemporal variations in palaeo-climate of eastern Azerbaijan in the Miocene generally match with prior climatic reconstructions (for example, seasonal warm to moderately humid) derived

![Fig. 10. Carbon–sulphur–iron (C–S–Fe) distributions and environmental indicators (for example, element ratios and CIA values) of the argillaceous rocks from the Islam Dağ section. Oxidized samples are marked in red.](image)
from the study onshore marine deposits from northern Azerbaijan and adjacent areas (Jones & Simmons, 1996; Rögl, 1999; Hudson et al., 2008, 2016; Popov et al., 2008; Johnson et al., 2010).

**Palaeo-salinity**

The TOC/S (=C/S) ratio is often applied to determine the palaeo-salinity (and the oxygenation level) of environments that are represented by organic rich, fine-clastic sediments (Raiswell & Canfield, 2012). Average C/S ratios in non-marine samples (12.2 ± 13.9) are generally higher compared to marine samples (4.3 ± 6.4), because Fe-sulphides (for example, pyrite) are more abundant in pristine marine deposits than in the freshwater equivalents (Berner & Raiswell, 1984). For the Islam Dağ section, the C/S ratios obtained for non-oxidized samples vary in the range from 7 up to 998; thus not recording a clear stratigraphic trend. Nevertheless, the disappearance of pyrite in units 3 and 4 might be an indicator for increased freshwater conditions and related decrease of the sulphate concentration in the basin towards the middle Miocene, taking that the nature and amount of organic matter are similar in all sedimentary units (see TOC contents in Table S3 and the discussion in Hudson et al., 2016).

However, variations in microfossil and palynomorph assemblages as well as ichthyofaunal elements over the Islam Dağ section seem to be a more robust tracer for palaeo-salinity, although not specifically investigated in this study. However, findings of Clupeidae, Merluccidae and dinocysts in the lowermost part of the profile (unit 1) indicate sediment deposition in a ‘deep-water’ depression at ca 300 to 600 m water depth and under normal-marine conditions during the early Miocene. Changes in ichthyofaunal elements (Argentinidae, Syngnathidae, Stromateidae, etc.) towards unit 2 suggest sediment accumulation near to the coast line under normal-salinity conditions through the mid-early to late-early Miocene (Popov et al., 2008). Remnants of fish and insects, and plant debris, as well as ichthyofossils (phytoplankton is scarce) can be found in early-middle Miocene strata and suggest polyhaline depositional environments (Popov et al., 2008), which matches with the deposition of gypsiferous argillites (unit 3) under evaporitic conditions. Occurrences of Spiratella and of different endemic species (Popov et al., 2008) in the uppermost part of the Islam Dağ section indicate restricted shelf basins and seasonal brackish to polyhaline conditions throughout the middle Miocene. These changes in palaeo-salinity coincide well with the proposed aridification and freshening events established on the basis of chemical proxies (Fig. 10), facies changes observed across the Islam Dağ section (i.e. shift from the deposition of carbonate-free argillites in a deep-basin setting to sedimentation of calcareous and gypsiferous argillites in a partly evaporitic, shallow water environment; Fig. 2) and with sedimentological and palaeontological analyses of carbonate argillites from the Spiralisian Formation and Upper Miocene Diamtom Suite (Ershov et al., 2003). This study suggests that seasonal freshening may be attributed to humid climate and freshwater input by the Palaeo-Volga and Palaeo-Don rivers.

**Palaeo-redox conditions**

Carbon–sulphur–iron associations and Fe/Al ratios can be used to constrain the oxygenation level in marine sediments, as these proxies typically reflect fluxes in the detrital or hydrothermal input, primary bioproductivity and benthic shuttling of Fe during and after deposition. Based on the study of 13 outcrop localities in eastern Azerbaijan, Johnson et al. (2010) have shown that the C–S–Fe distributions are predominated by the contribution of detrital Fe, especially in the Palaeo-Eocene and middle to late Miocene strata, where the TOC and pyrite-S contents are low (<1 wt. %). All Oligo–Miocene samples display higher amounts of TOC (up to 6.3 wt. %; Hudson et al., 2008) and pyrite-S (ca 1 to 2 wt. %; Johnson et al., 2010).

The argillites from the Islam Dağ section exhibit generally high TOC contents (4.9 ± 0.8 wt. %), low pyrite-S contents (0.17 ± 0.22) and S/Fe ratios significantly smaller than that of pyrite (for example, 0 to 0.2 versus 1.15). This indicates that most of the Fe is present in Fe-bearing silicates and labile Fe-oxyhydroxides, as indicated before. Taking that hydrothermal sources for Fe are not available and that the contribution of Fe by the volcanic ash deposits is minor (i.e. only four and thin laminae of volcanic ash were recognized in the studied profile; Fig. 2), it can be inferred that the major input of Fe is of detrital origin (i.e. bound to illite and minor chloride and Fe-oxyhydroxides). Regarding the nature of organic matter in the argillites, the presence of ubiquitous amounts of terrestrial higher plant material as well as evidence from δ13Corg isotope and the
SUMMARY AND CONCLUSIONS

The early to middle Miocene sedimentary succession of the Islam Dağ section in the Gobustan–Absheron depression (eastern Azerbaijan) was deposited in a restricted marine to lacustrine basin with pronounced recurrent periods of poorly oxygenated conditions, intensified evaporation and freshening events. The succession consists of organic-rich argillaceous rocks, accumulated during phases of high influx of siliciclastic and volcanogenic components from Russian Platform and Greater Caucasus source areas, respectively, with intercalated thin siltstone lenses, siderite concretions, volcanic ash layers and mudstone beds, deposited during phases of low detrital input. Detrital indicators, weathering indices and palynomorph assemblages reveal varying arid or semi-arid to moderately humid climates and related alternating polyhaline and euhaline to evaporative conditions in the depositional basin, concurrent with large-scale fluctuations in palaeogeography, orogenic activity and basin configuration in the Cenozoic. Trends in C–S–Fe distributions and Fe/Al ratios suggest high detrital inputs of Fe-illite, Fe-oxyhydrates and total organic carbon in a mostly well-oxygenated water column as well as significant syngenetic Fe scavenging through Fe(III)–smectite formation. Microbial heterotrophic and abiotic reduction of sulphate and Fe-oxyhydrates immediately at the sediment–seawater interface caused pyrite precipitation under reducing conditions, which further suppressed the oxidation of organic matter, making these offshore deposits excellent oil source rocks, compared to time-equivalent onshore deposits. In conclusion, this study illustrates the potential of the deposits of the Islam Dağ section to be used for regional-scale palaeo-environmental reconstruction of the Miocene Eastern Paratethys and for lithostratigraphic correlation with other onshore deposits, taken that this succession is largely unaffected by pedogenesis, cementation and compaction. Significant post-depositional alteration, such as oxidation of pyrite and formation of jarosite, the conversion of volcanic ash into smectite and zeolite and the formation of carbonates associated with meteoric diagenesis, can smear the sediment’s pristine signatures, thus hampering the interpretation of depositional and palaeo-environmental trends recorded in proxies based on isotopes. Future work focusing on the in-depth characterization of the
petrographic, mineralogical and chemical signatures of Miocene onshore and offshore deposits of the Euxinic–Caspian basins is needed to constrain the regional-scale response of the Eastern Paratethys to plate tectonics, weathering paths and climate change.

ACKNOWLEDGEMENTS

We greatly acknowledge the assistance of N. Shiyanova (BP Caspian) during several seasons of field campaigns. A. Leis (JR-AquaConSol GmbH) is acknowledged for providing the $\delta^{18}O$ and $\delta^{13}C$ isotope data. We also thank M. Abdullayev for supporting the SEM–EDS analyses (Institute of Geology and Geophysics, ANAS). The thoughtful comments and suggestions of two reviewers, A. Riboulleau, and one anonymous, and of the editors, C. Reid and P. Pufahl, were highly appreciated. This research was financially supported by the NAWI Graz and by the Lighthouse Geo Azerbaijan Branch.

REFERENCES

Abdullayev, E. and Leroy, S.G. (2016) Provenance of clay minerals in the sediments from the Pliocene Productive Series, western South Caspian Basin. Mar. Pet. Geol., 73, 517–527.

Anderson, T.F. and Arthur, M.A. (1983) Stable isotopes of oxygen and carbon and their application to sedimentologic and palaeoenvironmental problems. In: Stable Isotopes in Sedimentary Geology (Eds M.A. Arthur, T.F. Anderson, I.R. Kaplan, J. Veizer and L.S. Land), SEPM Short Course Notes, 10, 1–151.

Baldermann, A., Grathoff, G.H. and Nickel, C. (2012) Micromilieu-controlled glauconitization in fecal pellets at Oker (Central Germany). Clay Mineral., 47, 513–538.

Baldermann, A., Warr, I.N., Grathoff, G.H. and Dietzel, M. (2013) The rate and mechanism of deep-sea glauconite formation at the Ivory Coast-Ghana Marginal Ridge. Clay Clay Mineral., 61, 258–276.

Baldermann, A., Dohrmann, R., Kaufhold, S., Nickel, C., Letofsky-Papst, I. and Dietzel, M. (2014) The Fe-Mg-saponite solid solution series – a hydrothermal synthesis study. Clay Mineral., 49, 391–415.

Baldermann, A., Warr, I.N., Letofsky-Papst, I. and Mavromatis, V. (2015a) Substantial iron sequestration during green-clay authigenesis in modern deep-sea sediments. Nat. Geoscr., 8, 885–889.

Baldermann, A., Deditius, A.P., Dietzel, M., Fichtner, V., Fischer, C., Hippler, D., Leis, A., Baldermann, C., Mavromatis, V., Stickler, C.P. and Strauss, H. (2015b) The role of bacterial sulfate reduction during dolomite precipitation: implications from Upper Jurassic platform carbonates. Chem. Geol., 412, 1–14.

Baldermann, A., Dietzel, M., Mavromatis, V., Mittermayer, F., Warr, I.N. and Wemmer, K. (2017) The role of Fe on the formation and diagonsis of interstratified glauconite-smectite and illite-smectite: a case study of Upper Cretaceous shallow-water carbonates. Chem. Geol., 453, 21–34.

Baldermann, A., Landler, A., Mittermayer, F., Letofsky-Papst, I., Steinidl, F., Galan, I. and Dietzel, M. (2019) Removal of heavy metals (Co, Cr, and Zn) during calcium–aluminium–silicate–hydrate and trioctahedral smectite formation. J. Mater. Sci., 54, 9331–9351.

Baldi, T. (1980) The early history of the Paratethys. Földt. Közl. Bull. Hung. Geol. Soc., 110, 456–472.

Baron, D. and Palmer, C.D. (1996) Solubility of jarosite at 4–35 degrees C. Geochim. Cosmochim. Acta, 60, 185–195.

Bechtel, A., Movsumova, U., Strobl, S.A.I., Sachsenhofer, R.F., Soliman, A., Gratzer, R. and Püttemann, W. (2013) Organofacies and palaeoenvironment of the Oligocene Maikop series of Angelhan (eastern Azerbaijan). Org. Geochem., 56, 51–67.

Bechtel, A., Movsumova, U., Pros, J., Gratzer, R., Coric, S. and Sachsenhofer, R.F. (2014) The Oligocene Maikop series of Lahij (eastern Azerbaijan): Palaeoenvironment and oil-source rock correlation. Org. Geochem., 71, 43–59.

Beck, W.C., Grossman, E.L. and Morse, J.W. (2005) Experimental studies of oxygen isotope fractionation in the carbonic acid system at 15°, 25°, and 40°C. Geochim. Cosmochim. Acta, 69, 3493–3503.

Berner, R.A. and Raiswell, R. (1984) C/S method for distinguishing freshwater from marine sedimentary rocks. Geology, 12, 365–368.

Boch, R., Wang, X., Kluge, T., Leis, A., Lin, K., Pluch, H., Mittermayer, F., Baldermann, A., Böttcher, M.E. and Dietzel, M. (2018) Aragonite-calcite veins of the ‘Erzberg’ iron ore deposit (Austria): environmental implications from young fractures. Sedimentology, 66, 604–635.

Böttcher, M.E. and Parafiniuk, J. (1997) Methane-derived carbonates in a native sulfur deposit: stable isotope and trace element discriminations related to the transformation of aragonite to calcite. Isotopes Environ. Health Stud., 33, 177–190.

Bout-Roumazeilles, V., Riboulleau, A., Armynot du Châtelet, E., Lorenzoni, L., Tribovillard, N., Murray, R.W., Müller-Karger, F. and Astor, Y.M. (2013) Clay mineralogy of surface sediments as a tool for deciphering river contributions to the Cariaco Basin [Venezuela]. J. Geophys. Res. Oceans, 118, 750–761.

Buryakovskiy, L.A., Chilingar, G.V. and Aminzadeh, F. (2001) Petroleum Geology of the South Caspian Basin. Butterworth-Heinemann, Boston, 442 pp.

Canfield, D.E., Thamdrup, B. and Hansen, J.W. (1993) The anaerobic degradation of organic matter in Danish coastal sediments: iron reduction, manganese reduction, and sulfate reduction. Geochim. Cosmochim. Acta, 57, 3867–3883.

Chamley, H. (1989) Clay Sedimentology. Springer Verlag, Berlin, 623 pp.

Chen, F.H., Liu, J.B., Xu, Q.H., Li, Y.C., Chen, J.H., Wei, H.F., Liu, Q.S., Wang, Z.L., Cao, X.Y. and Zhang, S.R. (2013) Environmental magnetic studies of sediments cores from Conghai lake: implications for Monsoon evolution in North China during the Late Glacial and Holocene. J. Paleolimnol., 49, 447–464.

Craig, H. (1965) The measurement of oxygen isotope palaeotemperatures. In: Stable Isotopes in Oceanographic Studies and Palaeotemperatures (Ed. E. Tongiorgi), pp. 161–182. Consiglio Nazionale delle Richerche. Labortorio di Geologia Nucalee, Pisa, Italy.
Devlin, W.J., Cogswell, J.M., Gaskins, G.M., Isaksen, G.H., Pitcher, D.M., Pulz, D.P., Stanley, K.O. and Wall, G.R.T. (1999) South Caspian Basin: young, cool, and full of promise. Geol. Soc. Am. Today, 9, 1–9.

Dietzel, M., Tang, T., Leis, A. and Köhler, S.J. (2009) Oxygen isotopic fractionation during inorganic calcite precipitation – effects of temperature, precipitation rate and pH. Chem. Geol., 268, 107–115.

Epstein, S., Buchsbaum, R., Lowenstam, H.A. and Urey, H.C. (1953) Revised carbonate water isotopic temperature scale. Geol. Soc. Am. Bull., 64, 1315–1326.

Ershaw, A., Brunet, M.-F., Nikishin, A.M., Bolotov, S.N., Nazarevich, B.P. and Korotaev, M.V. (2003) Northern Caucasus basin: thermal history and synthesis of subsidence models. Sed. Geol., 156, 95–118.

Esquevin, J. (1969) Influence de la composition chimique des sédiments sur la cristallinité. Bull. Cent. Rech. Pau. SNPA, 3, 147–153.

Feyzullayev, A.A., Guliyev, I.S. and Tagiyev, M.F. (2001) Source potential of the Mesozoic-Cenozoic rocks in the South Caspian Basin and their role in forming the oil accumulations in the Lower Pliocene reservoirs. Petrol. Geosci., 7, 409–417.

Forte, A.M., Whipple, K.X. and Cowgill, E. (2015) Drainage network reveals patterns and history of active deformation in the eastern Greater Caucasus. Geosphere, 11, 1343–1364.

Fuchtbauer, H. (1988) Sedimente und Sedimentgesteine. Schweitzerbaurt, Stuttgart, 1141 pp.

Golonka, J. (2004) Plate tectonic evolution of the southern margin of Eurasia in the Mesozoic and Cenozoic. Tectonophysics, 381, 235–273.

Guliyev, I.S., Tagiyev, M.F. and Feyzullayev, A.A. (2001) Geochemical characteristics of organic matter from Maikop rocks of eastern Azerbaijan. Lithol. Miner. Resour., 36, 280–285.

Hellwig, A., Voigt, S., Mulch, A., Frisch, K., Bartenstein, A., Pross, J., Gerdes, A. and Voigt, T. (2018) Late Oligocene to early Miocene humidity change recorded in terrestrial sequences in the Ili Basin (south-eastern Kazakhstan, Central Asia). Sedimentology, 65, 517–539.

Hofer, G., Wagreich, M. and Neuburger, S. (2013) Geochemistry of fine-grained sediments of the upper Cretaceous to Paleogene Gosau Group (Austria, Slovakia): implications for paleoenvironmental and provenance studies. Geosci. Front., 4, 449–468.

Horton, T.W., Deflise, W.F., Tripati, A.K. and Oze, C. (2016) Evaporation induced 18O and 13C enrichment in lake systems: a global perspective on hydrologic balance effects. Quat. Sci. Rev., 131(Prat B), 365–379.

Hudson, S.M., Johnson, C.L., Efendiyeva, M.A., Rowe, H.D., Feyzullayev, A.A. and Chingiz, S.A. (2008) Stratigraphy and geochemical characterization of the Oligocene-Miocene Maikop Series: implications for the paleogeography of eastern Azerbaijan. Tectonophysics, 451, 40–55.

Hudson, S.M., Johnson, C.L. and Afandiyeva, M.A. (2016) Spatial and temporal variability of Paleocene-Miocene organofacies of the Kura Basin, eastern Azerbaijan, and implications for basin evolution and petroleum generation. Org. Geochem., 97, 131–147.

Johnson, C.L., Hudson, S.M., Rowe, H.D. and Efendiyeva, M.A. (2010) Geochemical constraints on the Paleocene-Miocene evolution of eastern Azerbaijan, with implications for the South Caspian basin and eastern Paratethys. Basin Res., 22, 735–755.

Jones, R.W. and Simmons, M.D. (1996) A review of the stratigraphy of Eastern Paratethys (Oligocene-Holocene). Bull. Nat. Hist. Mus. London Geol., 52, 25–49.

Key, M.M., Zágorsek, K. and Patterson, W.P. (2013) Paleo-environmental reconstruction of the Early to Middle Miocene Central Paratethys using stable isotopes from bryozoan skeletons. Int. J. Earth Sci. (Geol. Rundsch.), 102, 305–318.

Kotler, J.M., Hinman, N.W., Yan, B., Stoner, D.L. and Scott, J.R. (2008) Glycine identification in natural jaroisites using laser desorption Fourier transform mass spectrometry: implications for the search for life on Mars. Astrobiology, 8, 253–266.

Krhovsky, J., Hladikova, J. and Maslowska, H. (1993) Paleo-environmental changes across the Eocene/Oligocene boundary in the Zdanice and Pouzdrany Units (Western Carpathians, Czechoslovakia): the long-term trend and orbitally forced changes in calcareous nannofossil assemblages. In: Nannoplankton Research, Proceedings of the 4th International Nannoplankton Association Conference (Eds B. Hamsrnid and J.R. Young), Knihovnieka Zemni Plyn Nafta, Hodonin, pp. 105–187.

Lavrushin, V.Y., Guliev, I.S., Kikvadze, O.E., Ayiev, A.A., Pokrovsky, B.G. and Polyak, B.G. (2015) Waters from mud volcanoes of Azerbaijan: isotopic-geochemical properties and generation environments. Lithol. Miner. Resour., 50, 1–25.

Lawrence, J.R., Drever, J.I., Anderson, T.F. and Brueckner, H.K. (1979) Importance of alteration of volcanic material in the sediments of Deep Sea Drilling Site 323: chemistry, 18O/16O and 87Sr/86Sr. Geochim. Cosmochim. Acta, 43, 573–588.

Lewis, J.M.T., Najorka, J., Watson, J.S. and Septon, M.A. (2018) The search for Hesperian organic matter on Mars: pyrolysis studies of sediments rich in sulfur and iron. Astrobiology, 18, 454–464.

Mackenzie, F.T. (2005) Sediments, Diagenesis, and Sedimentary Rocks, 7: Treatise on Geochemistry. Geochim. Cosmochim. Acta, 207, 139–153.

McLennan, S.M., Hemming, S., McDaniel, D.K. and Hanson, G.N. (1993) Geochemical approaches to sedimentation, provenance, and tectonics. Geol. Soc. Am. Spec. Pap., 284, 21–40.

Nadir, A.A., Aghdamin, S.F., Khaiti, R. and Moghaddam, A.A. (2018) The problem of identifying arsenic anomalies in the basin of Sahand dam through risk-based ‘soft modelling’. Sci. Total Environ., 613–614, 693–706.

Nesbitt, H.W. and Young, G.M. (1982) Early Proterozoic climate and plate motions inferred from major element chemistry of lufites. Nature, 299, 715–717.

Nesbitt, H.W. and Young, G.M. (1984) Prediction of some weathering trends of plutonic and volcanic rocks based on thermodynamic and kinetic considerations. Geochim. Cosmochim. Acta, 48, 1523–1534.

Parafiniuk, J., Siuda, R. and Borkowski, A. (2016) Sulphate and arsenate minerals as environmental indicators in the weathering zones of selected ore deposits, Western Sudetes, Poland. Acta Geol. Pol., 66, 493–508.
Pearce, T.J., Wray, D., Ratcliffe, K., Wright, D.K. and Moscariello, A. (2005) Chemostratigraphy of the Upper Carboniferous Schorner Formation, southern North Sea. In: Carboniferous Hydrocarbon Geology: The Southern North Sea and Surrounding Onshore Areas (Eds J.D. Collinson, D.J. Evans, D.W. Holliday and N.S. Jones), Yorkshire Geological Society Occasional Publication, 7, 147–164.

Peckmann, J., Thiel, V., Michaelis, W., Clari, P., Gaillard, C., Martile, L. and Reitner, J. (1999) Cold seep deposits of Beauvoisin (Oxfordian; southeastern France) and Marmorito (Miocene; northern Italy): microbially induced authigenic carbonates. Int. J. Earth Sci. (Geol. Rundsch.), 88, 60–75.

Peryt, T.M., Durakiewicz, T., Peryt, D. and Poberezhsky, A. (2012) Carbon and oxygen isotopic composition of the Middle Miocene Badenian gypsum-associated limestones of West Ukraine. Geol. Acta, 10, 1–12.

Popov, S.V., Rogl, F., Rozanov, A.Y., Steininger, F.F., Shcherba, I.G. and Kovac, M. (2004) Lithological-Paleogeographic maps of Paratethys: 10 Maps Late Eocene to Pliocene. Paleogeographic maps of Paratethys: 10 Maps Late Eocene to Pliocene.

Popov, S.V., Sychevskaya, E.K., Akhmetiev, M.A., Zaporozhets, N.I. and Golovina, L.A. (2008) Stratigraphy of the Maikop Group and Pteropoda Beds in Northern Azerbaijan. Stratigr. Geol. Correl., 16, 664–677.

Popov, S.V., Antipov, M.P., Zastrozhnov, A.S., Kuirina, E.E. and Pinchuk, T.N. (2010) Sealevel fluctuations on the Northern Shelf of the Eastern Paratethys in the Oligocene-Neogene. Stratigr. Geol. Correl., 18, 200–224.

Poullon, S.W., Fralick, P.W. and Canfield, D.E. (2010) Spatial variability in oceanic redox structure 1.8 billion years ago. Nat. Geosci., 3, 486–490.

Pribyl, D.W. (2010) A critical review of the conventional SOC to SOM conversion factor. Geoderma, 156, 75–83.

Purgatscher, B., Dietzel, M., Baldermann, A. and Mavromatis, V. (2017) Control of temperature and aqueous Mg²⁺/Ca²⁺ ratio on the (trans-)formation of ikaite. Geochim. Cosmochim. Acta, 217, 128–143.

Raiswell, R. and Canfield, D.E. (2012) The iron biogeochemical cycle past and present. Geochem. Perspect., 1, 1–232.

Richoz, S., Baldermann, A., Frauwallner, A., Harzhauser, M., Daxner-Hock, G., Klammer, D. and Piller, W.E. (2017) Geochemistry and mineralogy of the Oligo-Miocene sediments of the Valley of Lakes, Mongolia. Paleobiodivers. Paleoenviron., 97, 233–258.

Rogl, F. (1999) Mediterranean and Paratethys. Facts and hypotheses of an Oligocene to Miocene Paleogeography (short overview). Geol. Carpath., 50, 339–349.

Roser, B.P. and Korsch, R.J. (1988) Provenance signatures of sandstone-mudstone suites determined using discriminant function analysis of major-element data. Chem. Geol., 67, 119–139.

Sachsenhofer, R.F., Hentschke, J., Bechtel, A., Coric, S., Gratzer, R., Gross, D., Horsfield, B., Rachetti, A. and Soliman, A. (2015) Hydrocarbon potential and depositional environments of Oligo-Miocene rocks in the Eastern Carpathians (Vrancea Nappe, Romania). Mar. Pet. Geol., 68[Part A], 269–290.

Sachsenhofer, R.F., Popov, S.V., Coric, S., Mayer, J., Misch, D., Morton, M.T., Pupp, M., Rauball, J. and Tari, G. (2018) Paratethyan petroleum source rocks: an overview. J. Petrol. Geol., 41, 219–246.

Singer, A. (1980) The paleoclimatic interpretation of clay minerals in soils and weathering profiles. Earth Sci. Rev., 15, 303–326.

Singer, A. (1984) The paleoclimatic interpretation of clay minerals in sediment – a review. Earth Sci. Rev., 21, 251–293.

Swart, P. (2015) The geochemistry of carbonate diagenesis: the past, present and future. Sedimentology, 62, 1233–1304.

Taylor, K.G. and Macquaker, J.H.S. (2011) Iron minerals in marine sediments record chemical environments. Elements, 7, 113–118.

Tucker, M.E. and Wright, V.P. (1990) Carbonate Sedimentology. Blackwell Science, Oxford, 482 pp.

Vandeginste, V., Swennen, R., Gleenon, S.A., Ellam, R.M., Osadetz, K. and Roure, F. (2009) Thermochemo sulphate reduction in the Upper Devonian Cairn Formation of the Fairholme carbonate complex (South-West Alberta, Canadian Rockies): evidence from fluid inclusions and isotopic data. Sedimentology, 56, 439–460.

Veizer, J. (1983) Trace elements and isotopes in sedimentary carbonates. In: Carbonates, Mineralogy and Chemistry (Ed. R.J. Reeder), Mineralogical Society of America, Reviews in Mineralogy, 11, 265–299.

Vincent, S.J., Morton, A.C., Carter, A., Gibbs, S. and Barabadzde, T.G. (2007) Oligocene uplift of the Western Greater Caucasus: an effect of initial Arabia-Eurasia Collision. Terra Nova, 19, 160–166.

Voigt, M., Pearce, C.R., Baldermann, A. and Oelkers, E.H. (2018) Stable and radiogenic strontium isotope fractionation during hydrothermal seawater-basalt interaction. Geochim. Cosmochim. Acta, 240, 131–151.

Washburn, A.M., Hudson, S.M., Selby, D., Abdullayev, N. and Shiyanova, N. (2018) Re-Os geochronology and chemostratigraphy of the Maikop series source rocks of eastern Azerbaijan. J. Petrol. Geol., 41, 411–416.

Manuscript received 10 January 2019; revision accepted 22 May 2019

Supporting Information

Additional information may be found in the online version of this article:

Table S1. Bulk mineralogy of argillaceous rocks from the Islam Dağ section (Shamakhy–Gobustan area, eastern Azerbaijan).

Table S2. Distribution of illite (Ilt), smectite (Smc), chlorite (Chl) and kaolinite (Kao) (in per cent) among the total clay mineral fraction (Clay) across the Islam Dağ section.

Table S3. Bulk geochemistry and δ¹⁸O and δ¹³C data of the Islam Dağ section (Shamakhy–Gobustan area, eastern Azerbaijan).