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Research paper

# Provenance of clay minerals in the sediments from the Pliocene Productive Series, western South Caspian Basin

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ABSTRACT

The research work presents clay mineral composition in the sediment of the Pliocene Productive Series from western South Caspian Basin and identify potential source areas for the different research regions. The Productive Series is a main reservoir unit in the South Caspian Basin and divided into a lower division and an upper division. The clay mineral assemblages document coinciding changes in provenance. At the time of the deposition of the Lower Division, the Russian Platform was a potential source area for the Absheron Peninsula and drained by Palaeo-Volga River. However, at the time deposition of the Upper Division three different sediment source could be identified for the three research areas: Absheron Peninsula – the Russian Platform was drained by the Palaeo-Volga; South Absheron Offshore Zone – the Greater Caucasus was drained by the Palaeo Samur River; Baku Archipelago – the Lesser Caucasus was drained by the Palaeo-Kura River.



## 1. Introduction

The Caspian Sea is the world's largest lake with a total area of 375,000 km$^2$ and is located in central Eurasia (Fig. 1. A; Abdullayev et al., 2012). During Oligocene and Miocene times, the Caspian Sea was a part of the Tethys between the Euro-Asian, Indian and Afro-Arabian plates. Paratethys and Mediterranean Seas were disconnected from each other at the peak of Messinian Salinity Crisis, 5.6–5.5 Ma. As a result water level of the Paratethys fell at least 50–100 m (Krijgsman et al., 2010). Further the Black Sea and the Caspian Sea, as part of the eastern Paratethys, separated in the late Miocene time (Krijgsman et al., 2010; Zubakov and Borzenkova, 1990). The development of an oceanic basin which formed the south Caspian Basin was caused by the more rapid rate of spreading (Smith-Rouch, 2006). The South Caspian basin, i.e. south of ca. 40° N, is located offshore Azerbaijan and is the oldest oil producing region in the world (Abrams and Narimanov, 1997). In 1848, the first oil well in the world was drilled in the Bibi-Eibat field on the Absheron Peninsula (Narimanov and Palaz, 1995). The main goal of exploration in the Absheron Peninsula, Absheron Archipelago, South Absheron Offshore Zone and Baku Archipelago in the Azerbaijan part of the Caspian Sea (Fig. 1. B; Kroonenberg et al., 2005) is to discover oil and gas fields within the non-marine clastic sedimentary sequence in the Pliocene Productive Series (Fig. 2. A).

The goal of the study is to investigate clay mineral composition of the Productive Series from the western South Caspian Basin in order to learn whether the clay mineral assemblages varies with stratigraphy. The main tool used in this study is clay minerals, to reconstruct sediment provenance and to establish the distribution of potential reservoir sediments.

The Productive Series (PS) is part of the Pliocene sequence and has a thickness of >5000 m (Abrams and Narimanov, 1997). Based on the microfauna composition, the PS is divided into a Lower Division and an Upper Division (Fig. 2. A). More humid climatic conditions occurred during the deposition of the Lower Division of the PS while more arid climatic ones occurred during deposition of the Upper Division (Hinds et al., 2004). Moreover according to the lithological composition, the Lower Division comprises the Kala Suite, Pre-Kirmaky Suite, Kirmaky Suite, Post-Kirmaky Sand Suite and Post-Kirmaky Clay Suite; and the Upper Division consists of the Fasila Suite, Balakhany Suite, Sabunchy Suite and Surakhany Suite (Fig. 2. A; Vincent et al., 2010; Reynolds et al., 1998). The PS is made up by alternating sandstones-siltstone-shale layers (Fig. 2 B; Hinds et al., 2004).

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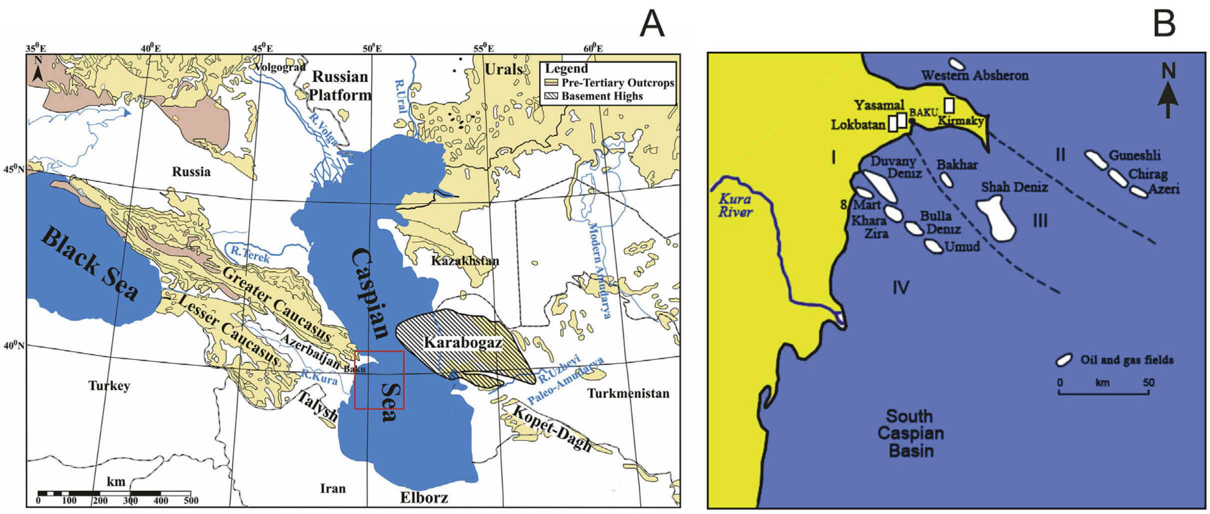


**Fig. 1.** A-Location map of the working area in the south Caspian Sea showing adjacent mountain belts and major river systems (Abdullayev et al., 2012), red box: research area; B-Location map of the four research areas with the main oil fields and subdivision into I-Absheron Peninsula, II-Absheron Archipelago, III-South Absheron Offshore Zone, IV-Baku Archipelago (after Kroonenberg et al., 2005). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

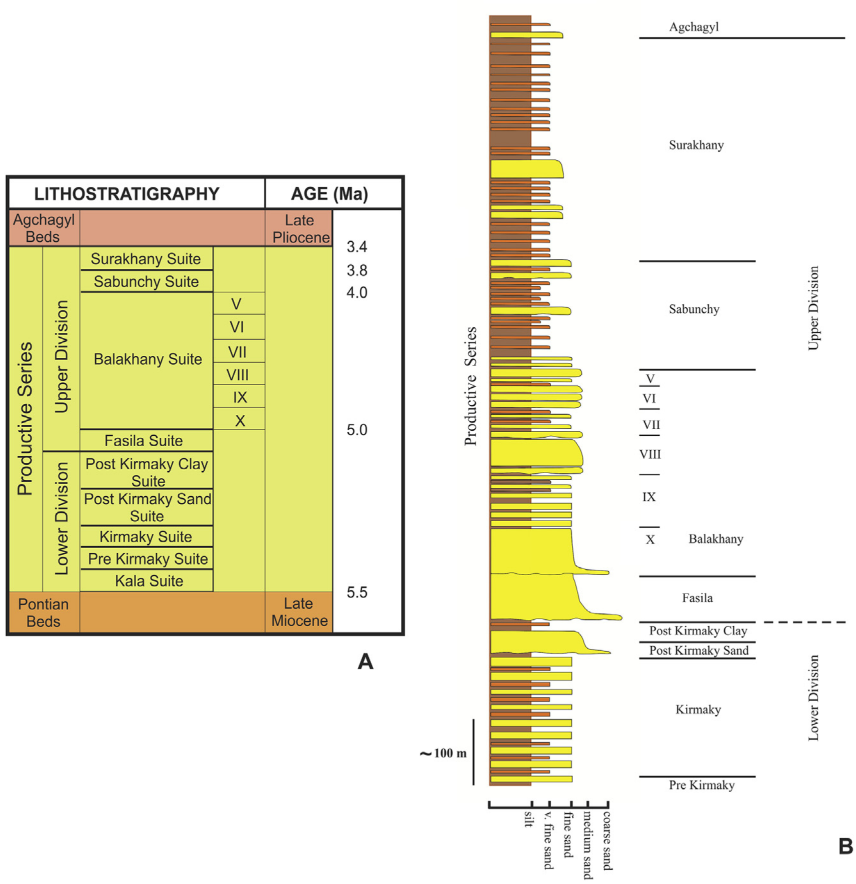


**Fig. 2.** A-Stratigraphic chart column of the Productive Series (after Vincent et al., 2010), B-simplified lithological column of the Productive Series on the Absheron Peninsula (Hinds et al., 2004).

## 2. Palaeo-drainages and source rocks

The western flank of the South Caspian basin was supplied with freshwater and terrigenous materials by the rivers from the Palaeo-Volga River system from the north and from the Palaeo-Samur and Palaeo-Kura river systems from the west at the time deposition of the Early Pliocene (Fig. 3; Khalifazade and Mursalov, 2007). These rivers are draining respectively the Russian platform, the Greater Caucasus and the Lesser Caucasus.

The Russian Platform in the North is characterised by

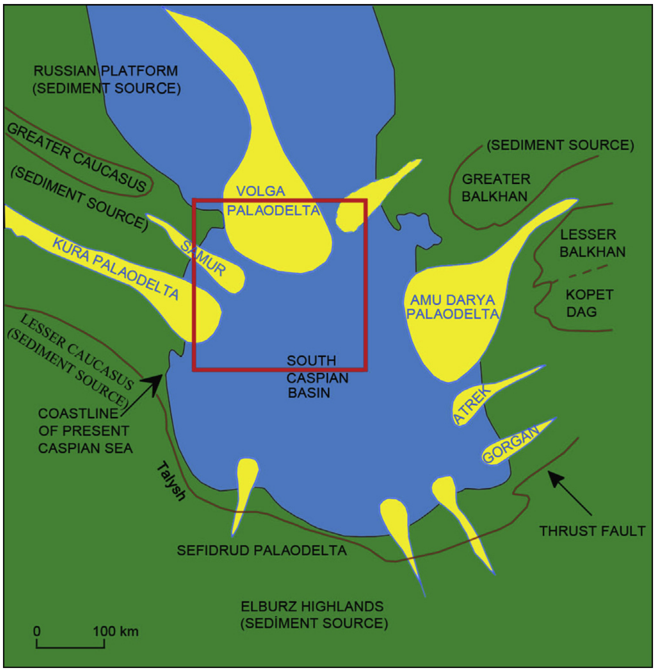


**Fig. 3.** Sketch of drainage systems during deposition of the Productive Series (after Smith-Rouch, 2006), red box: study area. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Precambrian, Palaeozoic and Mesozoic rocks (Mammadov and Karimov, 1987). The Precambrian sequences are represented by biotite-garnet-gneiss, garnet-gneiss, amphibolite, amphibolite-gneiss, beds of kaolinite, conglomerates and sandstones (Mammadov and Karimov, 1987). The Cambrian sequences are represented by quartz sandstones with clay lenses. The Ordovician deposits make up by carbonates, schist, dolomite and limestone. The Silurian, Devonian, Carboniferous and Permian deposits consist mainly of limestone, dolomite and marl (Mammadov and Karimov, 1987). The Triassic, Jurassic and Cretaceous deposits consist of sandstones and shale (Buryakovsky et al., 2001; Mammadov and Karimov, 1987).

The Greater Caucasus in the North-West is characterised by Jurassic and Cretaceous deposits (Buryakovsky et al., 2001). The Lower Jurassic rocks with the thickness >2000 m are widely distributed in the Greater Caucasus. They consist of sandstones, diabase and gabbro-diabase. The middle Jurassic deposits are divided into two parts. The lower part is composed by argillaceous rocks with rare sandstones and the upper part is composed by quartz sandstones with rare shale. The Upper Jurassic deposits consist mainly of calcarenites and reef limestones, whereas the Lower and the Upper Cretaceous deposits consist of terrigenous-carbonaceous flysch (Buryakovsky et al., 2001).

The Lesser Caucasus in the south-west consists mainly of Jurassic and Cretaceous deposits (Buryakovsky et al., 2001). The Lower Jurassic deposits are sparsely represented in the Lesser Caucasus. The lower part of the Middle Jurassic deposits are composed by lava sheets and diabasic volcanics. The upper part of the Middle Jurassic deposits consist of quartz-porphyry with their volcanoclastic sequences. The Upper Jurassic deposits are composed by reef limestones and volcanoclastic intervals. The Lower deposits consist of by reef limestones and volcanoclastic intervals. The Lower Cretaceous deposits of the Lesser Caucasus is represented by tuffaceous-terrigenous and carbonaceous rocks. The Upper Cretaceous deposits are composed by terrigenous-carbonaceous flysch (Buryakovsky et al., 2001).

The characterization of the possible source rocks in the south basin used so far the occurrence of mineral composition (Morton et al., 2003; Baturin, 1947).

## 3. Past investigations on clay minerals

The origins of the clay minerals distributed in sedimentary basins are divided into two categories, authigenic and detrital (Fagel, 2007; Chamley, 1989). Authigenic clay minerals result from post-depositional diagenetic changes and hydrothermal alteration (Weaver, 1989; Singer, 1984). Detrital clay minerals are weathering products of the initial rocks on the source areas (Chamley, 1989; Singer, 1984). The clay minerals, especially the detritics ones, are useful tools for studying the provenance of the sediments on the hinterland (Fagel, 2007; Thiry, 2000; Chamley, 1989; Singer, 1980). Previous studies show that clay mineral of detrital origin can be used to find source areas. Smectites are mainly derived by hydrolysis of feldspars (Chamley, 1989). Illite is derived from weathering of crystalline basement rocks rich in felsic silicates under dry climate (Weaver, 1989; Gradusov, 1974). Detrital chlorite mainly forms by physical weathering of plutonic and metamorphic rocks such as schist and gneiss by hydrolysis (Aghayev, 2006; Chamley, 1989). Detrital kaolinite forms by hydrolysis processes of K-feldspar, plagioclase and biotite (Aghayev, 2006; Khalifazade and Mammadov, 2003; Chamley, 1989; Pettijohn et al., 1987).

Several studies exist on the clay minerals of the PS sediments from the South Caspian Basin. Pashaly and Kheirov (1979) studied clay mineral assemblages of the PS and Red suite, i.e. the Pliocene sediments in the Turkmenistan region of the Caspian Sea. The study showed that amount of illite in the PS are increasing from the Baku Archipelago to Absheron Peninsula. The amount of illite of the PS from the Baku Archipelago is less than 40–45%, whereas in the Absheron Peninsula it is more than 50%. Further research by Turovskiy et al. (1981) showed that relatively high amounts of illite and relatively low amounts of smectite are found near the modern Volga River and the modern Samur River, whereas relatively low amounts of illite and relatively high amounts of smectite are found near the modern Kura river region. The high concentration in Zr, Rb, Th of clay minerals from the Pleistocene/Holocene of southern part from Caspian Sea indicate their detrital origin. The clay minerals (smectite, illite, chlorite, kaolinite) quartz and plagioclases of the sediments showed variation weathering/erosion processes in the middle of the south basin (Pierret et al., 2012).

## 4. Methods

For the present investigation, the samples were taken on the Absheron Peninsula (Kirmaky Valley and Yasamal Valley), Absheron Archipelago (Western Absheron), South Absheron Offshore Zone (Bakhar and Shah Deniz) and Baku Archipelago (8 Mart, Umud, Khara-Zira, Duvany Deniz) in the western South Caspian Basin. Specifically 144 samples from the outcrops of the Productive Series from onshore sites and 178 samples from drill cores recovered from the oil-gas-bearing zone from offshore site on the western South Caspian Basin were analysed at the University of Leipzig, Germany.

Scanning Electron Microscopy (SEM) was performed for identification of detrital versus authigenic origin of the smectite. The samples with high concentration were scanned with SEM CamScan Optics into 5–40 kV. The samples were placed on 12 mm diameter aluminium disc. The samples were coated with gold prior to investigation.

For X-ray analysis of clay minerals, 2.0–2.5 g of sediment were taken. The carbonate of the samples was removed by treatment with 10% acetic acid ($CH_3COOH$). Organic matter in the sediment

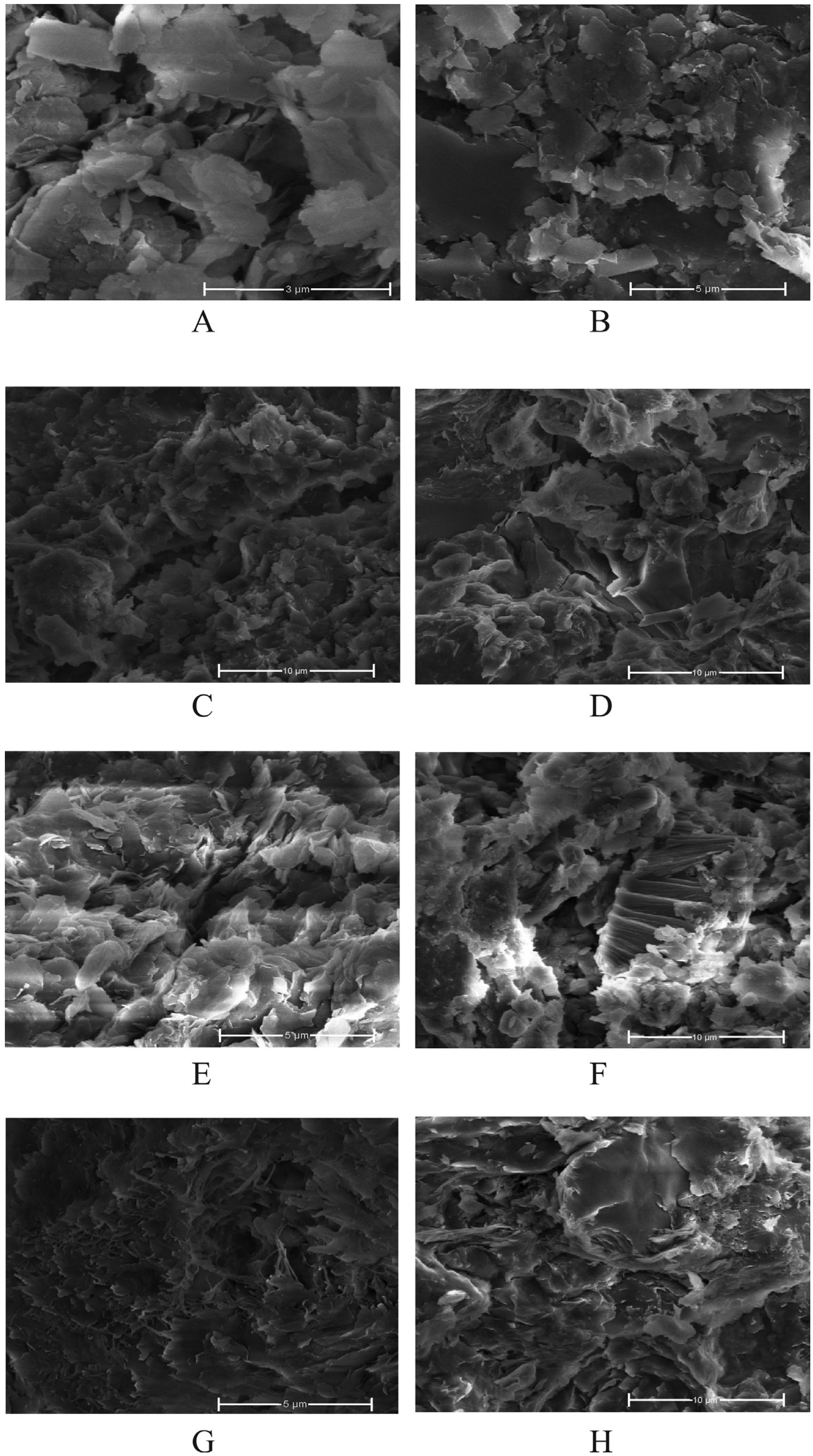


**Fig. 4.** SEM photographs of detrital smectites: Sabunchy Suite, 4903–4908 m, (A), (B), and (C). Balakhany Suite, 5129–5133 m, (D). Fasila Suite, 5382–5388 m, (E), (F). Post Kirmaky Clay 5493–5421 m (G), (H).

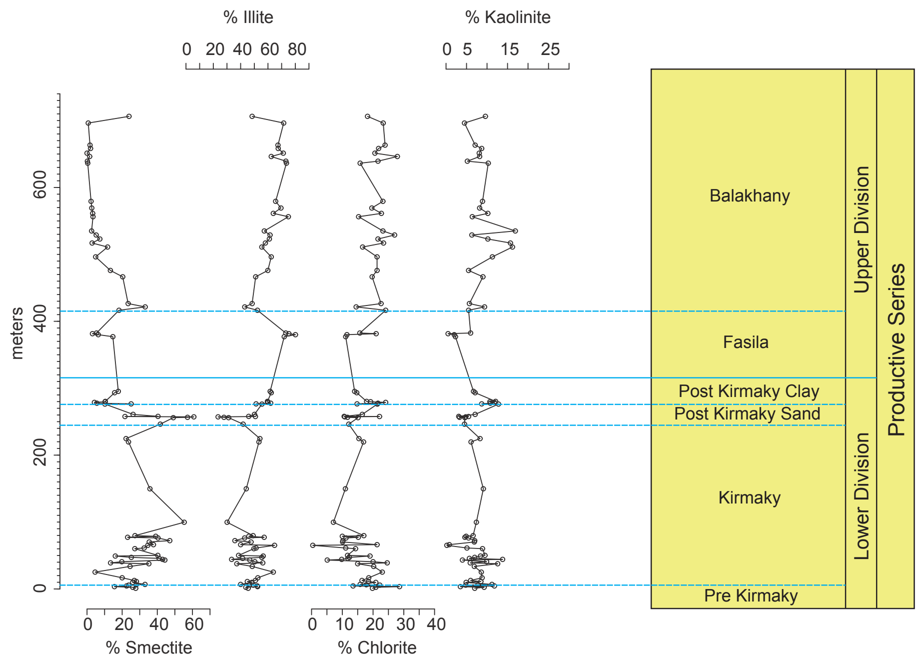


**Fig. 5.** Percentage distribution of the main clay mineral groups in the <2 μm fraction of the sediments of the Productive Series from Absheron Peninsula (Kirmaky Valley and Yasamal Valley).

was oxidized and disaggregated by means of a 5% hydrogen peroxide ($H_2O_2$) solution. For isolating the clay fraction (less than 2 μm) from the coarser fraction by the Atterberg method (settling time based on Stoke's Law), the samples were transferred to glass cylinders. 40 mg of clay suspension was mixed with 0.5 ml of an internal standard consisting of a 0.04% $MoS_2$ solution. After that process, the suspension was filtered through a membrane filter of 0.20 μm pore width. The filters were dried at 40 °C and mounted on aluminium tiles. The tiles were exposed to ethylene-glycol vapour at 60 °C for about 18 h before XRD analyses.

The samples were X-rayed in the range 3–40° 2θ with a step size of 0.02° 2θ and a measuring time of 2 s/step. Before being evaluated, the diffractograms were adjusted to the $MoS_2$ peak at 6.15 Å. Additionally, the range 27.5–30.6° 2θ was measured with a step size of 0.01° 2θ and a measuring time of 4 s/step in order to better resolve the (002) peak of kaolinite and the (004) peak of chlorite (Ehrmann, 1998).

We concentrated on the occurrence of the main clay mineral group illite, chlorite, kaolinite and smectite. These clay minerals

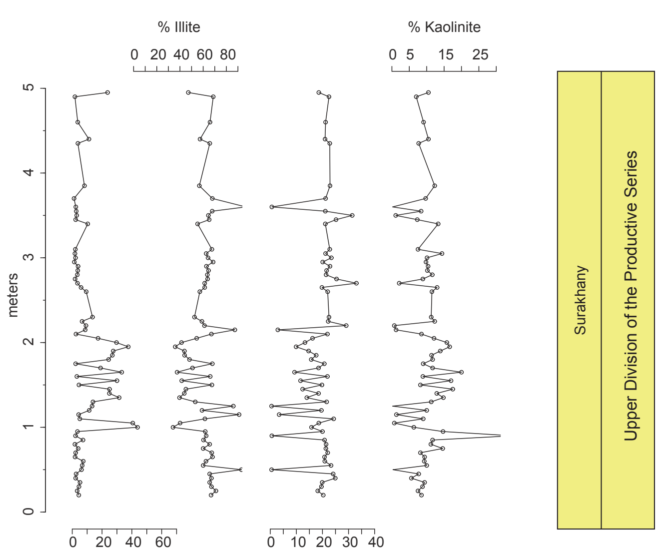


**Fig. 6.** Percentage distribution of the main clay mineral groups in the <2 μm fraction of the sediments of the Surakhany Suite from Absheron Peninsula (Yasamal Valley).

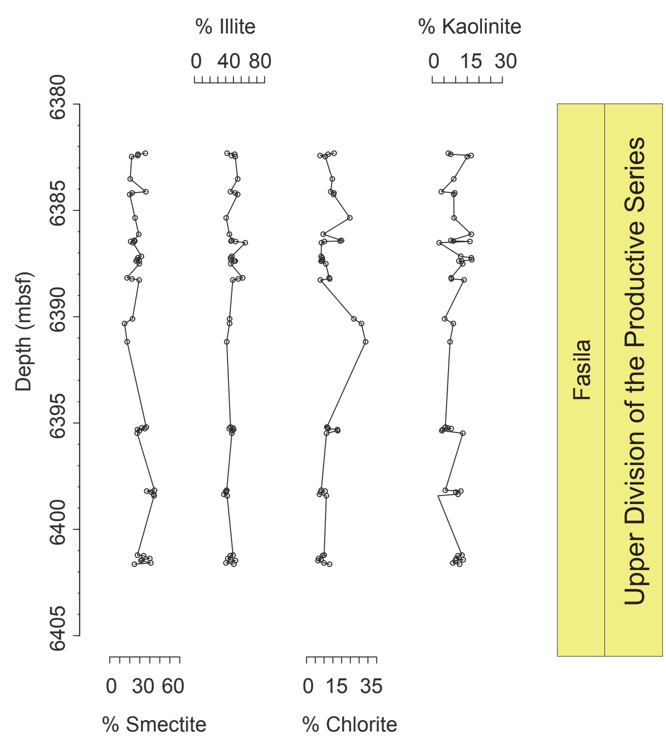


**Fig. 7.** Percentage distribution of the main clay mineral groups in the <2 μm fraction of the sediments of the Fasila Suite of the Productive Series from the South Absheron Offshore Zone (Shah Deniz).

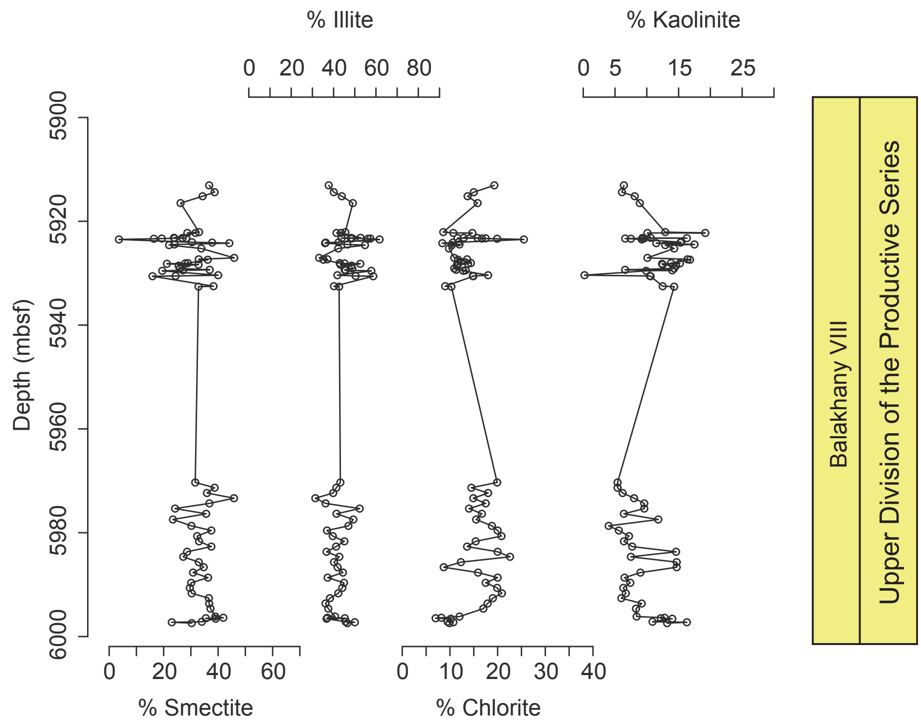


**Fig. 8.** Percentage distribution of the main clay mineral groups in the <2 μm fraction of the sediments of the Balakhany VIII sub-suite of the Productive Series from the South Absheron Offshore Zone (Shah Deniz).

were identified by their basal reflections at 10.0 and 5.0 Å (illite), 14.0, 7.0, 4.7 and 3.54 Å (chlorite), 7.0 and 3.58 Å (kaolinite), and 16.5 Å (smectite, after glycolation). The relative percentages of illite, smectite, chlorite and kaolinite were determined using empirically estimated weighting factors (Biscaye, 1964, 1965).

The d-spacing of the (060) reflection was recorded for the determination of illite polytypes (Kheirov, 2008; Tucker, 1988). The samples not treated with glycol were X-rayed in the range 57–74° 2θ with step size of 0.01° 2θ and measuring time of 1 s/step. If $2M_1$ illite is present, the d-spacing is between 1.48 and 1.50 Å.

Ternary plots of kaolinite-smectite-illite and illite-smectite-chlorite are used to distinguish between different sediment source areas for the PS from the different working areas. Each of the corners of the ternary diagram represent 100% of the clay mineral composition plotted at that corner and 0% of the other composition. In a ternary plot of kaolinite-smectite-illite, a line of the illite-smectite represents the illite composition, a line of the smectite-kaolinite represents kaolinite composition and the kaolinite-illite represents kaolinite composition. In ternary plots of illite-smectite-chlorite, a line of the illite-chlorite represents illite composition, a line of the chlorite-smectite represents chlorite composition and the smectite-illite represents smectite composition.

**Table 1**
Clay mineral groups in the <2 μm fraction of the sediments of the lower division of the Productive Series from Absheron Archipelago (Western Absheron).

| Depth (mbsf) | Suite | % Smectite | % Illite | % Chlorite | % Kaolonite |
|---|---|---|---|---|---|
| 800–805 | Post Kirmaky Clay | 45.2 | 39.4 | 5.8 | 9.6 |
| 5014–5020 | Post Kirmaky Sand | 33 | 49.1 | 11.7 | 6.2 |
| 563–568 | Kirmaky | 40.3 | 38.1 | 8.7 | 12.9 |
| 891–896 | | 17 | 57.9 | 16.3 | 8.8 |
| 900–907 | | 18.8 | 64.1 | 11.6 | 5.5 |
| 922–927 | | 46.3 | 36.2 | 7.2 | 10.3 |
| 1079–1084 | | 16.3 | 52.1 | 27.8 | 3.8 |
| 1093–1103 | | 27.7 | 45.2 | 15.3 | 11.9 |
| 1135–1140 | | 38.3 | 41.3 | 8.2 | 12.3 |
| 1072–1076 | Pre Kirmaky | 47.2 | 34.2 | 8.2 | 10.5 |
| 1152–1163 | | 26.4 | 53.8 | 12.6 | 7.2 |
| 1260–1265 | | 29.1 | 48.2 | 10.5 | 12.2 |
| 1449–1455 | | 27.4 | 50.3 | 11.7 | 10.6 |
| 1335–1339 | Kala | 36 | 60.5 | 3.5 | 0 |
| 1454–1457 | | 35.3 | 44.8 | 9 | 10.9 |
| 1552–1557 | | 45 | 34.2 | 9.2 | 11.6 |
| 1577–1582 | | 36.9 | 37.5 | 11.5 | 14.1 |
| 1604–1609 | | 33.5 | 43.9 | 10.4 | 12.2 |
| 1615–1620 | | 17.5 | 57.2 | 19.5 | 5.8 |
| 1650–1654 | | 51.1 | 32.3 | 5.5 | 11.1 |

**Table 2**
Clay mineral groups in the <2 μm fraction of the sediments of the Productive Series from the South Absheron Offshore Zone (Bakhar).

| Depth (mbsf) | Suite | % Smectite | % Illite | % Chlorite | % Kaolonite |
|---|---|---|---|---|---|
| 3205–3210 | Surakhany | 40.7 | 40.8 | 9.4 | 9.2 |
| 3259–3263 | | 41.2 | 35.1 | 12.5 | 11.2 |
| 3735–3738 | Balakhany | 2.8 | 53.8 | 38.7 | 4.8 |
| 3923–3926 | | 37.2 | 36.7 | 16 | 10.1 |
| 3924–3926 | | 22.8 | 35 | 15.8 | 26.4 |
| 4343–4350 | | 28.4 | 39.8 | 2.2 | 29.5 |
| 3996–3999 | | 36.4 | 38 | 16.9 | 8.7 |
| 4232–4238 | | 36.2 | 27.4 | 24.9 | 11.5 |
| 4359–4364 | | 27.8 | 34.3 | 25.6 | 12.3 |
| 4702–4707 | | 19.7 | 41.2 | 12.1 | 27 |
| 4269–4273 | | 29.6 | 33.4 | 25 | 12 |
| 4580–4585 | | 23.8 | 35.6 | 29 | 11.6 |
| 4598–4602 | | 25.9 | 52.6 | 11.9 | 9.5 |
| 4620–4625 | | 33.7 | 45.2 | 13.4 | 7.7 |
| 4556–4572 | Fasila | 3.8 | 66 | 29.2 | 1 |
| 5080–5085 | | 31.2 | 34.2 | 20.4 | 14.2 |
| 4818–4823 | Post Kirmaky Clay | 36.8 | 39.9 | 9.5 | 13.8 |
| 5165–5172 | | 13.6 | 60.4 | 18.8 | 7.2 |
| 5542–5545 | | 30.1 | 41.1 | 11.1 | 17.6 |
| 4818–4823 | Post Kirmaky Sand | 35.4 | 34.4 | 16.7 | 13.5 |
| 5003–5006 | Pre Kirmaky | 27.3 | 43.5 | 10.4 | 18.7 |

**Table 3**
Clay mineral groups in the <2 μm fraction of the sediments of the Productive Series from the Baku Archipelago.

| Depth (mbsf) | Suite | % Smectite | % Illite | % Chlorite | % Kaolonite |
|---|---|---|---|---|---|
| 2386–2391 | Surakhany | 40.7 | 44.9 | 9.7 | 4.6 |
| 3157–3160 | | 31.9 | 48.8 | 16.6 | 2.7 |
| 3875–3880 | | 37.7 | 32.4 | 19.5 | 10.4 |
| 3831–3836 | Sabunchy | 55.0 | 28.2 | 12.5 | 4.3 |
| 42354240 | | 47.8 | 40.0 | 10.4 | 1.8 |
| 4903–4908 | | 47.1 | 36.3 | 10.0 | 6.6 |
| 5527–5532 | | 32.8 | 40.6 | 15.5 | 11.1 |
| 3419–3422 | Balakhany | 54.1 | 34.2 | 3.9 | 7.9 |
| 3710–3714 | | 72.9 | 13.3 | 8.4 | 5.4 |
| 4697–4702 | | 37.3 | 40.9 | 16.8 | 5.0 |
| 4818–4824 | | 44.8 | 38.2 | 13.5 | 3.5 |
| 4950–4956 | | 54.5 | 28.1 | 11.4 | 6.0 |
| 5030–5035 | | 47.4 | 35.8 | 12.8 | 4.0 |
| 5100–5105 | | 34.0 | 26.3 | 30.6 | 9.2 |
| 5116–5119 | | 30.1 | 50.0 | 12.7 | 7.2 |
| 5129–5133 | | 51.7 | 31.1 | 12.9 | 4.3 |
| 5150–5155 | | 29.6 | 45.3 | 14.1 | 11.1 |
| 5175–5180 | | 44.2 | 36.7 | 13.0 | 6.2 |
| 5050–5053 | Fasila | 15.7 | 58.4 | 20.8 | 5.1 |
| 5382–5388 | | 47.0 | 37.0 | 13.0 | 3.0 |
| 5640–5645 | | 55.1 | 27 | 15.7 | 2.1 |
| 5416–5421 | Post Kirmaky Clay | 27.5 | 51.7 | 13.2 | 7.6 |
| 5493–5421 | | 30.1 | 50 | 12.7 | 7.2 |
| 4860–4862 | Kala | 54.1 | 34.2 | 3.9 | 7.9 |

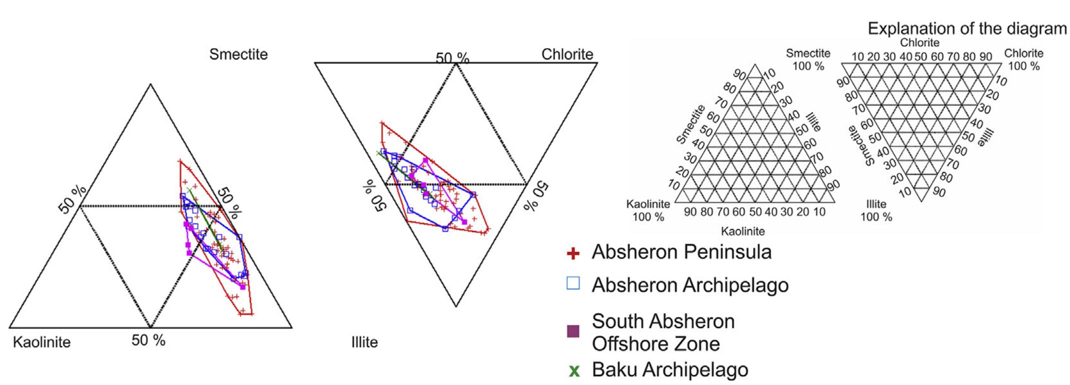


**Fig. 9.** Ternary diagrams showing the average clay mineral composition of sediments in the lower division of the Productive Series from the different working areas.

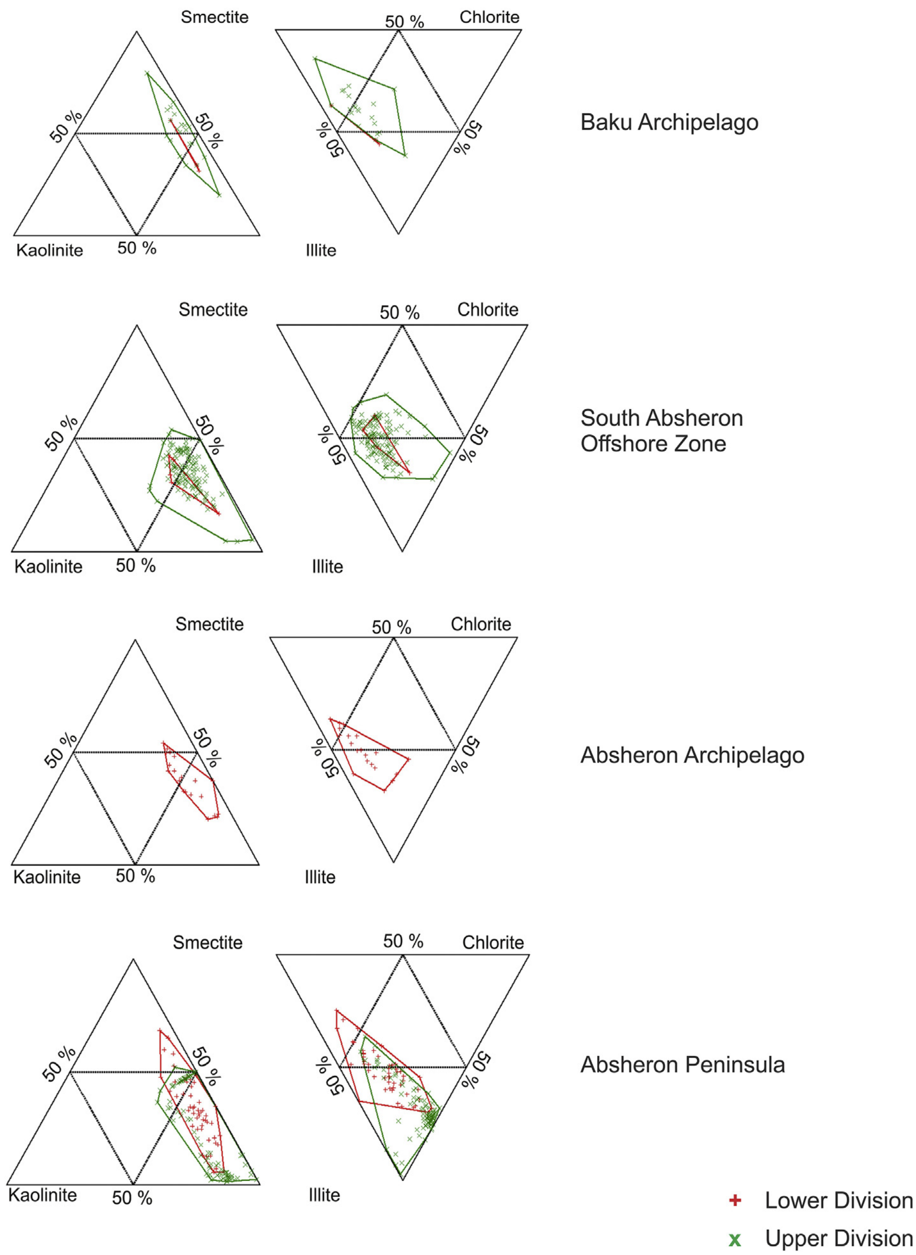


**Fig. 10.** Ternary diagrams showing the average clay mineral composition of the lower and the upper divisions of the Productive Series from the different working areas. For detail information of the axes see Fig. 9.

## 5. Results

According to SEM in samples of both the Lower Division and the Upper Division of the Productive Series, the Baku Archipelago shows structures with platy morphologies, smectite exhibiting cornflake structures and smectites coating detrital sediment grains (Fig. 4). These features are typical for detrital smectites. In contrast, we cannot see any features that are typical authigenic smectites, such as honeycomb smectites, hairy shapes, overgrowth of smectite on grain surface or smectite cement growth in the pore space of the sediments. Thus, the overwhelming part of the smectites seems to be of detrital origin.

The results of the percentage distribution of the main clay minerals are shown on Figs. 5–8. Because samples from different areas of the western South Caspian Basin were investigated, the diagrams were shown separately for each region. The result of the Surakhany Suite from Absheron Peninsula are also presented separately because from the suite only a profile of 5–6 m thickness was sampled, however with a spacing of 5 cm.

Tables 1–3 of the clay minerals data from Absheron Archipelago (Western Absheron), South Absheron Offshore Zone (Bahar) and Baku Archipelago has been chosen, because the samples cannot be brought into strict stratigraphic order.

## 6. Discussion

The result of the our analysis and previous studies clearly showed that the clay minerals of the PS from Absheron Peninsula, Absheron Archipelago, South Absheron Offshore Zone and even from Baku Archipelago are detrital origin (Pashaly and Kheirov, 1979; Turovskiy et al., 1981).

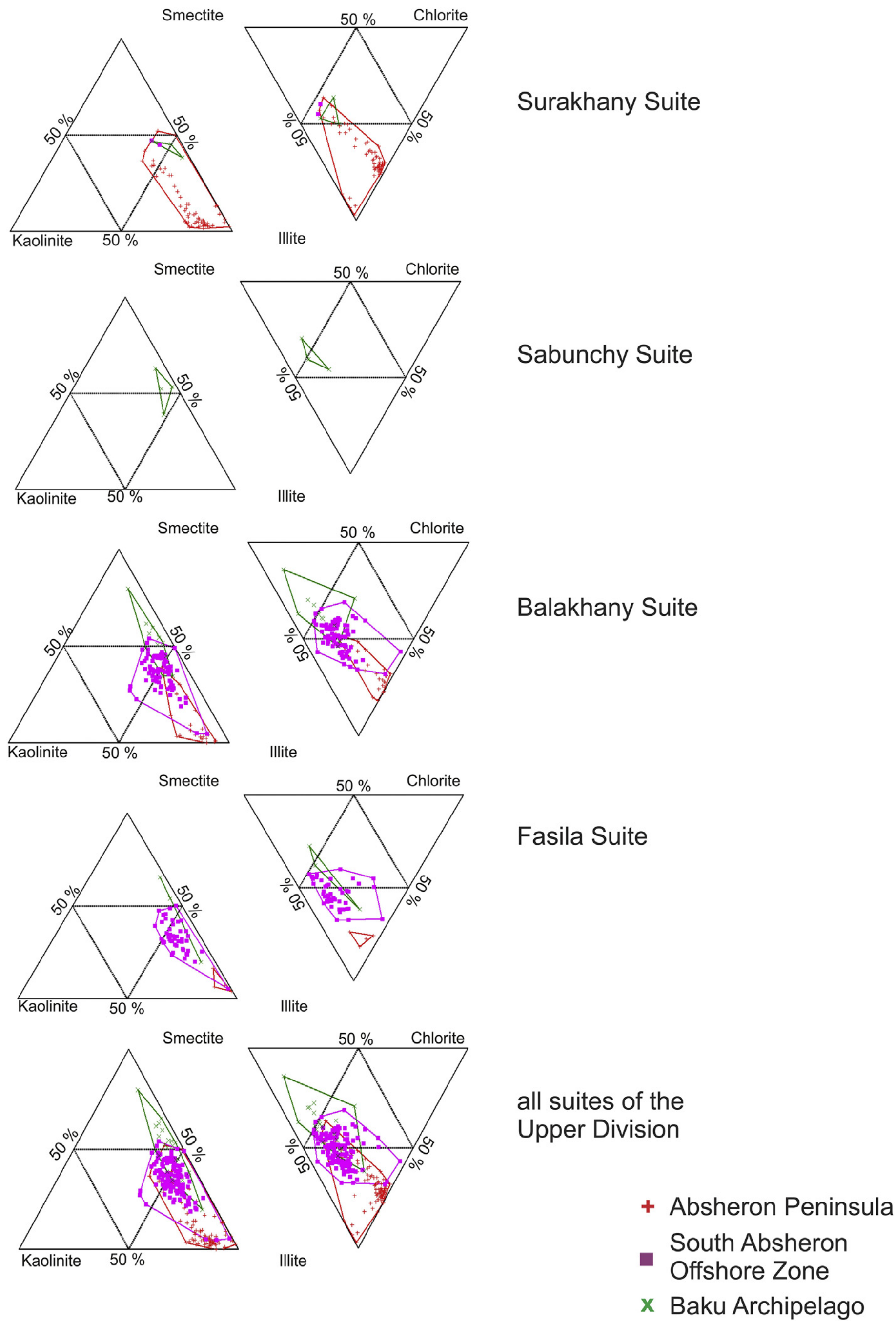


**Fig. 11.** Ternary diagrams showing the average clay mineral composition of sediments in individual suites of the upper division of the Productive Series from the different working areas. For detail information of the axes see Fig. 9.

### 6.1. ***Lower*** *division sediment input from the Russian platform*

The Lower Division of the PS from different working areas is characterised by a similar composition and therefore probably have the same source areas (Fig. 9). The clay mineral assemblages have potential source in the Russian Platform that was drained by the Palaeo-Volga River (Baturin, 1947; Turovskiy et al., 1981). Illite and chlorite are mainly derived from the physical weathering of biotite-garnet, garnet-gneiss of Precambrian sequences in the Russian Platform. Smectite and kaolinite may be provided from the weathering of shale of Jurassic and Cretaceous deposits in the Russian Platform.

### 6.2. ***Upper*** *division of the PS*

The clay mineral assemblages of the Upper Division from the different research areas have a different composition. Specifically, the clay mineral composition of the Upper Division consists of higher amounts in illite and kaolinite than the Lower Division. This indicates that the clay minerals of the different research areas are provided from different sources.

#### 6.2.1. *Absheron Peninsula –* ***Upper*** *division sediment input from the Russian platform*

The clay mineral assemblages of the Upper Division on the

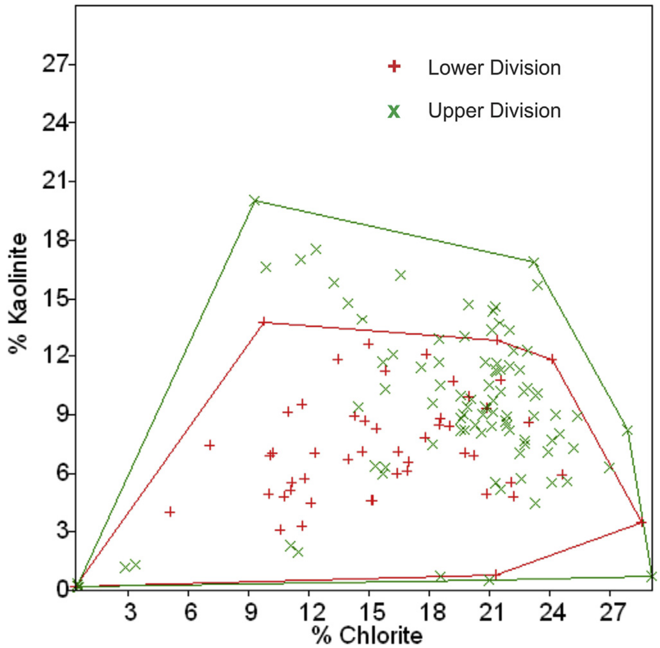


**Fig. 12.** Kaolinite-Chlorite crossplots for the Productive Series on the Absheron Peninsula.

Absheron Peninsula have a generally high content of illite and low content of smectite (Figs. 10–11). The composition is similar to the modern Volga and the Palaeo-Volga clay mineral assemblages (Turovskiy et al., 1981). The clay minerals were derived from the Russian Platform. The high amount of illite suggests physical weathering of the biotite-garnet gneiss in the Russian Platform. Sediment of the Upper Division shows higher maxima in the amount of kaolinite (Fig. 12). This suggests that kaolinite-bearing Precambrian beds in the Russian Platform became a more important source at the time.

### *6.2.2. South Absheron offshore zone — **Upper** division sediment input from the Greater Caucasus*

The Upper Division have a mixed assemblage of illite and smectite and higher amounts of chlorite than kaolinite (Figs. 10–11). The clay mineral assemblage differs from that of Absheron Peninsula by a generally lower illite content. It might indicate a lower influence of Palaeo-Volga River and the Russian Platform. Thus Palaeo-Volga did not reach the South Absheron Offshore Zone. We suggest that the Greater Caucasus was drained by the Palaeo-Samur River delivering more chlorite. The reduced influence of the Palaeo-Volga is explained by arid climatic condition in the Russian Platform, which causes a lower activity of the Palaeo-Volga River at the time of deposition of the Upper Division (Khalifazade and Mursalov, 2007). Alternatively the palaeo-Volga has shifted its course and flowed away from the area. Illite and chlorite result from the weathering of the flysch of the Upper Cretaceous sequences on the hinterland. Smectite and kaolinite mainly derived by the weathering of sedimentary units such as argillaceous rock and shales of the middle Jurassic sequences in the Greater Caucasus.

### *6.2.3. Baku Archipelago — **Upper** division sediment input from the Lesser Caucasus*

Sediments of the Upper Division on the Baku Archipelago have higher smectite concentrations than on the Absheron Peninsula and in the South Absheron Offshore Zone (Figs. 10–11). The composition of the clay minerals suggests that sediments of the Upper Division have potential source in the Lesser Caucasus which was drained by Palaeo-Kura River system (Turovskiy et al., 1981). The high smectite content may be derived by weathering of terrigenous rocks of the Middle Jurassic. In addition smectite might be provided by alternation of volcanogenic rocks.

The concept based on clay mineral composition for different research areas correspond to the idea by Baturin (1947) which is based on mineralogical composition of the PS. Our concept also suggested, as Baturin (1947), that the Russian Platform was a potential source for the PS from the Absheron Peninsula and materials of the deposits from the Greater Caucasus and the Lesser Caucasus were not founded in the sediments. Materials from the Russian platform are mainly characterized by disthene, staurolite, sillimanite which are not found in the Greater Caucasus and the Lesser Caucasus.

The results by Morton et al. (2003) based on heavy minerals and Allen et al. (2006) based on zircon data do not coincide with the results derived from clay minerals. According to Morton et al. (2003), both the Russian Platform and the Greater Caucasus were sediment sources during the early stages of the Productive Series. The zircon data also suggested that the Russian Platform and the Greater Caucasus were potential source for the Productive Series in Absheron area (Allen et al., 2006). However clay minerals assemblages characteristic for the Greater Caucasus (relatively high amount of chlorite) were not found in the PS of the Absheron Peninsula. Moreover the Palaeo-Kura could not reach the Absheron Peninsula as suggested Morton et al. (2003) because sediment delivered from the Lesser Caucasus represented by high amount of smectite are not found in the Upper Division of the PS from the Absheron Peninsula.

## 7. Conclusions

The clay minerals of the PS from the research areas have a detrital origin. According to clay mineral assemblages of the PS, different sediment source areas are clearly distinguished for the Lower and the Upper Divisions.

The Lower Division sediments have the same clay mineral composition in different research areas, which suggests a potential unique sediment source in the Russian Platform. The Russian Platform was drained by the Palaeo-Volga River system.

The Upper Division sediments, characterized by different clay mineral compositions in different research areas, suggest that the clay minerals are derived from different sources. The Upper Division sediments from the Absheron Peninsula (I in Fig. 10) have potential source in the Russian Platform that was drained by the Palaeo-Volga River. The clay mineral assemblages from the South Absheron Offshore Zone suggest that the potential source for the Upper Division sediments was the Greater Caucasus that was drained by the Palaeo-Samur River. The sediment of the Upper Division from the Baku Archipelago was delivered by the Palaeo-Kura River from the Lesser Caucasus.

Reconstruction of the provenance based on the clay mineral assemblages agree with the concept by Baturin (1947). However our concept does not agree with Morton et al. (2003) and Allen et al. (2006) because the high amount of chlorite, that is a characteristic for the Greater Caucasus and the high amount of smectite that is characteristic for Palaeo-Kura river sediment, were not found in the PS from Absheron Peninsula. The Russian Platform was the only source area for the sediment of the PS from the Absheron Peninsula and was mainly derived by Palaeo-Volga River.

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