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Title:

Effects of clay minerals on reservoir quality: a case study of western South Caspian Basin

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Abstract

Clay minerals like kaolinite, smectite, illite, chlorite are widespread in oil and gas targeted rocks. The mineralogical composition is significant, especially when it comes to clay, which has many components that are particularly appealing to petroleum engineers. Clay minerals are believed to be damaging to the quality of sandstone reservoirs because they can block pore throats by creating films, plates, and bridges on the grain surface, and some clay minerals increase chemical compaction. Porosity and permeability are the two most important parameters of reservoir quality. The influence of clay minerals on reservoir quality is thoroughly summarized in this work.

Despite the fact that there have been several reports concerning the use of clay minerals in oil and gas exploration. So far, only a small amount of research has been done on the description of clay minerals from the perspective of reservoir performance. There are some studies done before concerning the distribution, classification, and origin of clay minerals in the South Caspian Basin. The goal of the study is to identify the effect of the detrital clay mineral on porosity and permeability in Lower Pliocene Productive Series sediments from the western South Caspian Basin. The Shah-Deniz gas field that is located in the South Caspian Sea, is the subject of our research. The Shah Deniz gas field is Azerbaijan's greatest natural gas field. Shah Deniz's field was studied by composing mineralogical composition of clay minerals and petrophysical data from the Fasila and Balakhany VIII.

Xülasə

Kaolinit, smektit, illit, xlorit gil mineralları neft və qaz süxurlarda geniş yayılmışdır. Gilin mineraloji tərkibi xüsusilə neft mühəndisləri üçün çox əhəmiyyətlidir. Adətən, gil minerallarının rezervuarın keyfiyyətinə zərər verdiyi bilinir, çünki onlar məsamə boğazlarını bağlaya bilirlər və bununla birqə məsəməliki ve keçiriciliki azalda bilərlər. Məsaməlik və keçiricilik rezervuar keyfiyyətinin ən vacib iki parametridir. Bu elmi işdə gil minerallarının rezervuar keyfiyyətinə (məsaməlik və keçiricilik parametrlərinə) təsiri hərtərəfli ümumiləşdirilmişdir.

Baxmayaraq ki, neft və qaz kəşfiyyatında gilli faydalı qazıntıların istifadəsi ilə bağlı bir neçə elmi işlər görülüb, indiyədək gil minerallarının rezervuar performansı nöqteyi-nəzərindən təsviri ilə bağlı az miqdarda tədqiqat aparılıb. Məsələn, bu gunə qədər Cənubi Xəzər hövzəsində gil minerallarının yayılması, təsnifatı və mənşəyi ilə bağlı bir neçə tədqiqatlar aparılmışdır. Bu tədqiqatın məqsədi isə qərbi Cənubi Xəzər hövzəsinin Aşağı Pliosen Məhsuldar Qat çöküntülərində gil mineralının (kaolinit, smektit, illit, xlorit) məsaməlik və keçiriciliyə təsirini müəyyən etməkdir. Cənubi Xəzər dənizində yerləşən Şahdəniz qaz yatağında Balaxanının VIII və Fasilə lay dəstələri Cənubi Abşeron zonasında gil minerallarının xüsusiyyətləri və paylanması və onların layların keyfiyyətinə təsiri elmi işin mövzusudur. Şahdəniz qaz yatağı Azərbaycanın ən böyük təbii qaz yatağıdır. Şahdəniz yatağının gil minerallarının mineraloji tərkibi və Balaxanı VIII və Fasilədən əldə edilən petrofiziki məlumatlar əsasında tədqiq edilmişdir.

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1. Introduction

The phrase "clay mineral" refers to a variety of minerals that are hydrous aluminous phyllosilicates, whereas "clay" is primarily a grain-size term, referring to particle diameters less than 3.9 µm (Worden & Morad, 2003). The terms "clay" and "clay mineral" are commonly used interchangeably in sedimentary petrology (Worden & Morad, 2003). Clay minerals are made of crystalline particles that are divided into groups based on their crystal structure. Clay minerals occur in weathering crusts, continental and marine sediments, most often in shales, volcanic deposits, and low-grade metamorphic rocks. They are formed in a wide range of environmental conditions, including weathering, rock type, topography, and the presence of organisms and organic materials (Galán & Ferrell, 2013).

Kaolinite, chlorite, smectite, illite, and mixed layer ones are common fine-grained clays found in sandstones and carbonates. In reservoir sandstones, these clay minerals are found as both detrital matrix and authigenic cement (Fagel, 2007). Detrital clay minerals are derived from erosion and weathering products of the primary rocks in the source areas. Authigenic clay minerals form after hydrothermal alternation and diagenesis in the basin (Fagel, 2007). As clay minerals are widely spread and dominate the fine fractions of rocks, they play an important role in regulating subsurface fluid movement.

The most essential parameters that define and influence reservoir performance qualitatively and quantitatively are reservoir petrophysics, such as porosity, permeability, water saturation, and hydrocarbon saturation. Because the grain size of clay minerals is typically quite small, resulting in very low effective porosity and permeability, any presence of clay in a reservoir can have significant effects on reservoir parameters (Said et al. 2003). The capability of the rock to accumulate and transport reservoir fluids, or simply petrophysical properties of the reservoir is necessary to determine two valuable parameters: porosity, and permeability. These parameters determine how much oil and gas a rock can hold and how quickly that oil and gas can be extracted. Detailed knowledge of porosity and permeability distribution within reservoir rocks helps identify high-quality zones and select optimal well locations. Porosity determines the volume of reservoir fluids accumulated by the rock, measuring the pore space in percentage. Thus, permeability refers to the connection of pores and measures the flow of reservoir fluids between these pore spaces.

Clay minerals' importance from the perspective of oil and gas exploration covers topics such as diagenesis, depositional environment, thermal and maturity of source rock, oil and gas generation, and migration and quality of reservoir prediction (Jiang, 2012). Rock characteristics such as porosity, permeability, density, natural radioactivity, water content, and resistance to different enhanced oil recovery methods are all affected by the quantity, distribution pattern, and morphology of clay minerals (Worden & Morad, 2003). Clay minerals are commonly thought to be harmful to reservoir quality because they can block pore throats by forming films, plates, and bridges on the grain surface, also some clay minerals increase chemical compaction. The diagenetic clay minerals, in particular, play an important role in defining reservoir quality. The diagenetic process, which includes mechanical compaction, quartz, and K-feldspar overgrowths, carbonate cementing, and clay mineralization is the major source of porosity reduction. However, clay minerals can also enhance reservoir quality by creating, for example, secondary porosity, and also important to note that various clay-mineral may have a different effect on permeability and porosity (Jiang, 2012).

Despite the fact that there have been several works that have discussed the distribution, classification, and provenance of the clay minerals in the South Caspian Basin (Kosovsgoy,1954; Pashaly and Kheirov, 1979; Turovskiy et al., 1981; Buryakovsky et al, 1995; Abdullayev and Leroy 2016, 2017), so far, only a small amount of research has been done on the description of clay minerals from the perspective of oil and gas exploration. This study aims to provide the impact of the detrital clay mineral on reservoir characteristics, such as porosity and permeability in the Lower Pliocene sediments from the western South Caspian Basin. The Lower Pliocene that is called the Productive Series in the western South Caspian Basin is the main reservoir unit (Buryakovsky et al., 1995).

Fig. 1 The schematic location map of the study area

The South Caspian Basin is the southern section of the Caspian Sea, with a total size of 375.000 km is the world's largest lake. Iran, Azerbaijan, Russia, Kazakhstan, and Turkmenistan border the Caspian Sea which is located in south-central Eurasia. (Fig. 1). The South Caspian Basin is one of the world's oldest hydrocarbon resource regions and a key petroleum supplier to the European market (Buryakovsky et al., 1995). The first oil well in the world was drilled in 1848, in the Bibi-Eibat field on the Absheron Peninsula. At the end of the 19th century, the first offshore well of Azerbaijan was drilled.

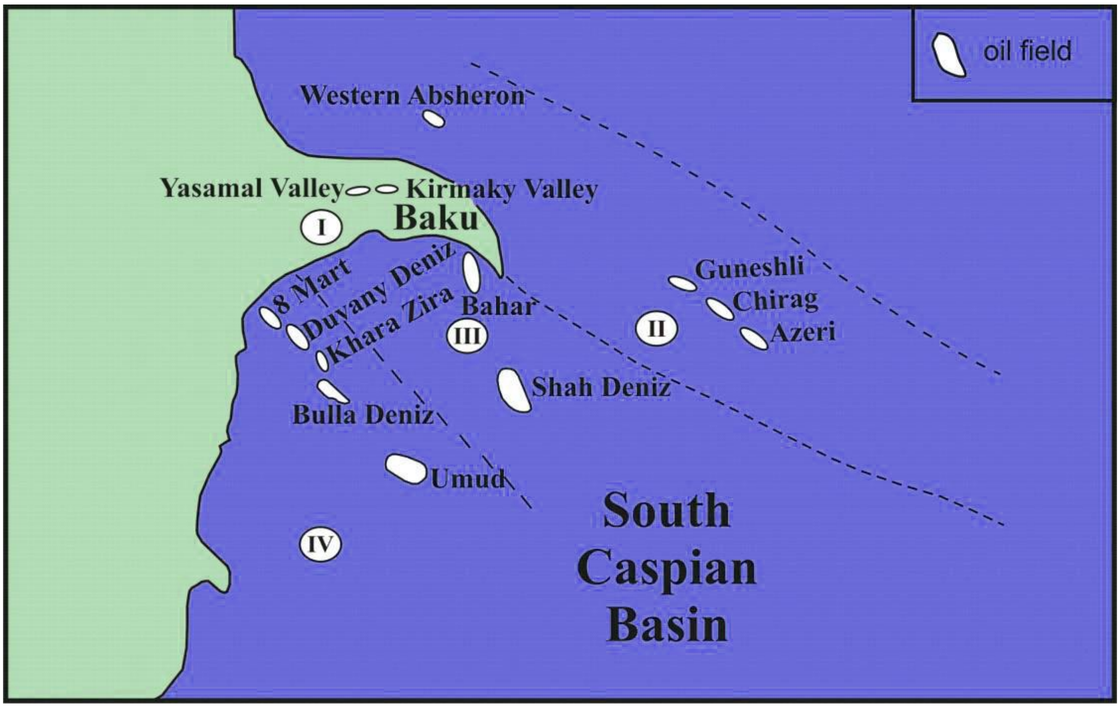


Fig. 2. Location map of the research area with the main oil fields and its subdivision into I-Absheron Peninsula, II-Absheron Archipelago, III-South Absheron Offshore Zone, IV-Baku

The research area of Azerbaijan part of the Caspian Sea is subdivided into 4 parts: I-Absheron Peninsula, II-Absheron Archipelago, III-South Absheron Offshore Zone, IV-Baku Archipelago (Fig. 2) (Buryakovsky et al.,1995). The main goal of exploration is to discover oil and gas fields within the sedimentary sequence in the Pliocene Productive Series.

The Absheron Peninsula is a significant oil resource in Azerbaijan's onshore area. The majority of the onshore oil fields are located in the peninsula's central region (Fig. 2) (Buryakovsky et al.,1995). Absheron Archipelago consists of large offshore fields such as Azeri, Chirag, Guneshli. (Fig. 2). Pre Kirmaky and Kirmaky Suites are the most productive sequence in the region (Buryakovsky et al.,2001). Large offshore hydrocarbon fields of Azerbaijan are located in the South Absheron Offshore Zone. In the Absheron Offshore Zone around 120 wells were drilled in the Bahar field. Balakhany Suite of the Upper Division is the most productive sequence for the Bahar field (Buryakovsky et al., 2001).

In our research, we focus on studying the Shah-Deniz gas field. Shah Deniz gas field is the largest natural gas field in Azerbaijan. It is located in the South

Caspian Sea, roughly 70 kilometers southeast of Baku, at a depth of 600 meters, off the coast of Azerbaijan. The field is about 860 square kilometers. The Shah Deniz field's three primary gas reservoirs are the sandstones of Balakhany VIII formation and the Sandy Packages II and III of the Fasila group. In 1999, Shah Deniz began drilling its first exploration and appraisal wells intended to evaluate and identify the field's reserves. At the close of the 20th century, deep hydrocarbon accumulations below 5000 meters were identified in the South Caspian basin. They mainly concentrated on two structures: Fasila Suite and the Balakhany VIII sub-suite, which are the foundations of the field's early development. 22.1 trillion cubic feet of gas and 750 million barrels of condensate are estimated to be recoverable in the first stage of development (Javanshir et al., 2015).

2. Geology of Azerbaijan and the South Caspian Basin

The folded systems that make up Azerbaijan's landmass include the eastern sections of the Greater and Lesser Caucasus Mountains, the Kura Intermontane Depression (Kura Lowland) that separates them, and the Middle and South Caspian basins. The thickness of the Earth's crust here varies between 38 and 55 kilometers. The Greater Caucasus has the most thickness, while the Talysh foothills have the least. The crustal thickness reaches 40 to 45 km in the Lesser Caucasus' submontane area, and 50 km in the Kura Intermontane Depression (Buryakovsky et al., 2001). A flysch-filled depression on the southern slope of the Greater Caucasus with substantial growth of overlaying structures is one of the folded system's peculiarities. Early Jurassic shaly copper-pyrite deposits can be found in isolated locations. Mesozoic-Early Paleogene and Late Paleogene-Quaternary formations are distinctly separated within the Kura Intermontane Depression. Within the folded system of the Lesser Caucasus in the south and the Vandam zone in the north, the first stage of Mesozoic volcanogenic-sedimentary rocks forms a single unit. The Lesser Caucasus was a volcanic zone during the Mesozoic, Paleogene, Miocene-Pliocene, and Quaternary periods, with a large ophiolitic belt in the middle part—the eastern component of the North Anatolia Belt. Azerbaijan has a lot of Jurassic and Cretaceous deposits (Buryakovsky et al., 2001).

Lower Jurassic deposits (thickness of 2,000 m or more) are extensively spread in the Greater Caucasus and are represented by slate and sandstone, with diabase and gabbrodiabase intrusive sheets. The Lower Jurassic is more sparingly represented in the Lesser Caucasus and the Nakhichevan area than its corresponding terrigenous facies. The Lower Jurassic deposits appear to be comparable, thin terrigenous facies within the Kura Depression. (Buryakovsky et al., 2001)

The Greater Caucasus' lowermost Middle Jurassic strata contain argillaceous slates with few sandstone partings, but the highest section (2,500 to 4,000 m thick) is characterized by thick strata and beds of quartz sandstones with rare shales partings. Lava sheets and diabasic volcanics make up the lowermost Middle Jurassic terrigenous rocks (thickness of 120 m) in the Lesser Caucasus [the major part of the section (2,000–3,000 m thick)] (Buryakovsky et al., 2001). The highest layers contain quartz plagio-porphyrites with volcaniclastic and sedimentary-volcanogenic phases. These deposits are characterized by facies that are identical throughout the Kura Depression (Buryakovsky et al., 2001).

Calcarenites and reef limestones (thickness of 300 m) make up the Upper Jurassic deposits on the northern slope of the Greater Caucasus, while flysch-like variegated, silicified, and carbonaceous shales make up the southern slope (thickness of 500 m). Reef limestone and volcanogenic-clastic intervals (500 - 1,500 m) make up these deposits in the Lesser Caucasus and the Kura Depression. Carbonaceous-terrigenous flysch (thickness 500–2,000 m) dominates the Lower Cretaceous deposits of the Greater Caucasus, whereas tuffaceous-terrigenous and carbonaceous intervals dominate the Lesser Caucasus and Kura Depression (Buryakovsky et al., 2001).

The Greater Caucasus' Upper Cretaceous deposits (thickness of 2,000 m) are composed of terrigenous-carbonaceous flysch facies. Their content has reduced in the Lesser Caucasus, but has considerably grown in the Kura Depression. The Kura and Araks depressions, Kusary sloping plain, Gobustan area, Apsheron peninsula, Talysh foothills, and a variety of residual and superimposed depressions in the Greater and Lesser Caucasus all have Paleogene, Neogene, and Quaternary deposits (Buryakovsky et al., 2001).

The major reservoir rocks for oil and gas accumulations in Azerbaijan are these deposits of substantial thickness in depressions. Green-gray, blocky shales with sandstone and marl partings make up the Paleogene deposits in the depressions. Deposits are 300–400 meters thick in the Pre-Caspian area, 1,700 meters thick in the Apsheron peninsula, and 2,800 meters thick in the Shemakha-Gobustan region. Paleogene deposits in the Kura Depression are distinguished by a thicker accumulation of more than 3,000 m (Buryakovsky et al., 2001). In areas near to the Greater Caucasus, Neogene deposits consist of sandy shale in the lower layers and shallow, thick sandstones and coquina in the upper strata. The thickness varies between 1,700 m (Pre-Caspian region) and 4,500 m (Apsheron peninsula) and 5,500 m (Apsheron peninsula) (Gobustan area). Marine, continental, and volcanogenic facies are found in Quaternary deposits. The heaviest accumulation is found inside the Lower Kura subdepression (more than 1,500 m), where shallow marine deposits dominate the lower layers, while alluvial and delluvial deposits predominate the higher strata (Buryakovsky et al., 2001).

The mentioned Phanerozoic deposits are buried inside the Middle and South Caspian basins, which are located to the east and southeast of Azerbaijan's landmass. These deposits are buried at high depths inside the South Caspian Basin, increasing the thickness of the Paleogene-Quaternary period. The Paleogene-Quaternary interval is 20 kilometers thick in the South Caspian Basin, near to the Lower Kura subdepression, according to geophysical data (Buryakovsky et al., 2001).

During the last stage of Alpine folding, the current structure of Azerbaijan and the South Caspian Basin formed. This explains why the current movement's structures are similar to old structural features. There is now active folding, diapirism, fracturing, seismicity, mud volcanism, geysers, and thermal springs in this area (Buryakovsky et al., 2001).

Azerbaijan geology is characterized by the existence of Middle Pliocene terrigenous strata 2,500–3,500 m thick (the Productive Series) with oil and gas reserves, as well as the wide distribution of mud volcanism in the south-eastern Caucasus and the offshore area of the South Caspian Basin (Buryakovsky et al., 2001).

3. Stratigraphic framework

The dramatic drop in base-level (of between 600 and 1500 m), most likely resulted in the accumulation of up to 7 km of the Productive Series sediment throughout 2.5 Ma (Ali-Zadeh et al., 1985; Green et al., 2009). Based on the micropaleontological data the Productive Series is divided into two parts: Upper and Lower. It's also subdivided into nine stratigraphic units based on lithological composition and sand-shale ratio. Kala Suite, Pre Kirmaky Suite, Kirmaky Suite, Post Kirmaky Sand Suite, and Post Kirmaky Clay Suite are all included in the Lower Division. Fasila Suite, Balakhany Suite, Sabunchy Suite, and Surakhany Suite are located in the Upper Division. This sub-division is based on lithological differences, and it appears to be in line with Soviet-era terminology. This suite includes major reservoir successions, onshore and offshore Azerbaijan (Reynolds et al., 1998). Suits and sub-suits can be identified regionally on wireline logs and exhibit distinct palynological signatures (Vincent et al., 2010). Generally, the stratigraphic series is built up by shifting sandstone-siltstone-shale layers (Hinds et al., 2004; Reynolds et al.,1998).

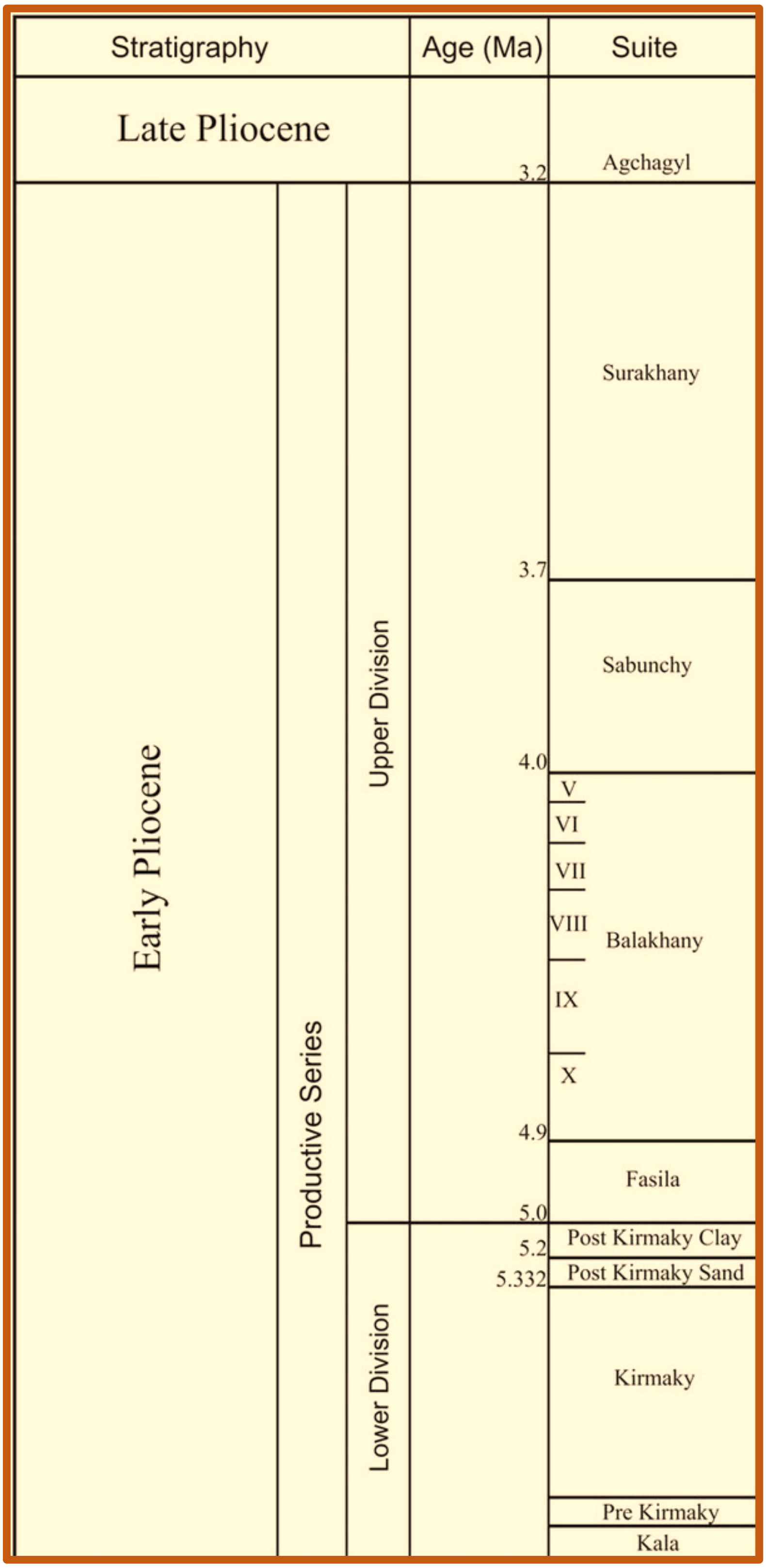


Fig. 3 Simplified lithological chart of The Productive Series (after Hinds et al., 2004; Forte & Cowgill, 2013)

The Post Kirmaky Sand Suite (Fig. 3) consists of sandstones with minor interbeds of shale. On Absheron Peninsula the thickness of the suite is 35-40 m, in Bahar field it increases to 60-70 m, with 60 % of the suite consisting of sandstones (Narimanov et al., 1998). The Kirmaky Suite consists dominantly of shales, with less amount of siltstones and sandstones and siltstones. The Post Kirmaky Clay Suite (Fig. 3) is built up by shales and loams (soil consisting of silt, sand, and a smaller amount of clay), with some thin sandstone/siltstone beds in the lower zones (Buryakovsky et al., 2001). The thickness of the suite in Bahar field is about 150 m and around 30-35 m on the Absheron Peninsula (Narimanov et al., 1998). The Fasila Suite (Fig. 3) is consists of shale and unsorted rocks consisting of sandstone. In Absheron Peninsula only 35 m are well exposed and consists of sandstones. In the Bahar field its increases up to 167 m (Abdullayev et al., 1998), and in the Azeri, Chirag, Guneshly the thickness of the suite is about 110 m (Reynolds et al., 1998).

The Balakhany Suite (Fig. 3) can be divided into six subunits: Balakhany V, VI, VII, VIII, IX, X. Suite consists of sandstones, siltstones, shales, childolites, loams, and loamy sand (Buryakovsky et al., 2001). The thickness is more than 300 m, in the Bahar field up to 586 m (Narimanov et al., 1998). The Sabunchy Suite (Fig. 3) consists of siltstones, sandstones, and shales. The thickness of the suite is about 200 m on Absheron Peninsula and in the Bahar field, it increases up to 477 m (Narimanov et al., 1998). The Surakhany Suite (Fig. 3) consists of sandstones, silty shales, siltstones, and unsorted rocks (Buryakovsky et al., 2001). On Absheron Peninsula its 500 m thick and in the Bahar field the thickness is 1647 m (Narimanov et al., 1998).

It is important to note that in characterizing the geological features of the southern Caspian Basin, sedimentary formations of Fasila and Balakhany VIII suites are the most important reservoir horizons in the research area's sedimentary sequences (Jafarzadeh et al., 2019).

4. Depositional environment

The first modern sedimentology-based study of the Productive Series outcrops was published by Reynolds et al. (1998). Four facies associations (fluvial, delta-plain, proximal delta-front, and distal delta-front) were interpreted by Reynolds et al. (1998) as a genetically connected set of depositional environments. The alternation of sandstone- and mudstone-dominated facies that characterize the Productive Series was interpreted by Reynolds et al. (1998) to indicate the frequent confrontation of proximal and distal fluvial-deltaic environments, mostly in reaction to high-frequency base-level variations.

Hinds et al. (2004) identified three different types of deposits in the Lower Division of the Productive Series based on systematic sedimentological analyses of the Absheron Peninsula: sheetflood fluvial deposits, lacustrine muds and channelized fluvial deposits. A cyclic deposition was observed. The fluvial system is indicated by channelized sandstones and floodplain mudstones. Lacustrine mudstones indicate that maximum humidity induced lacustrine extension and flooding of the alluvial plain.

The upper Productive Series deposits are considered to be a terminal fluvial system that expanded and contracted periodically throughout its alluvial plain but also experienced mild lacustrine impact. An increasing abundance of characteristics compatible with subaerial exposure and desiccation distinguishes the Upper Productive Series from the lower portion of the succession, notably in the Sabunchi and Surakhany suites. The architecture of the higher Productive Series suites does not exhibit the same degree of uniform interstratification of mudstone and sandstone packages as the Kirmaky Suite (Hinds et al., 2004).

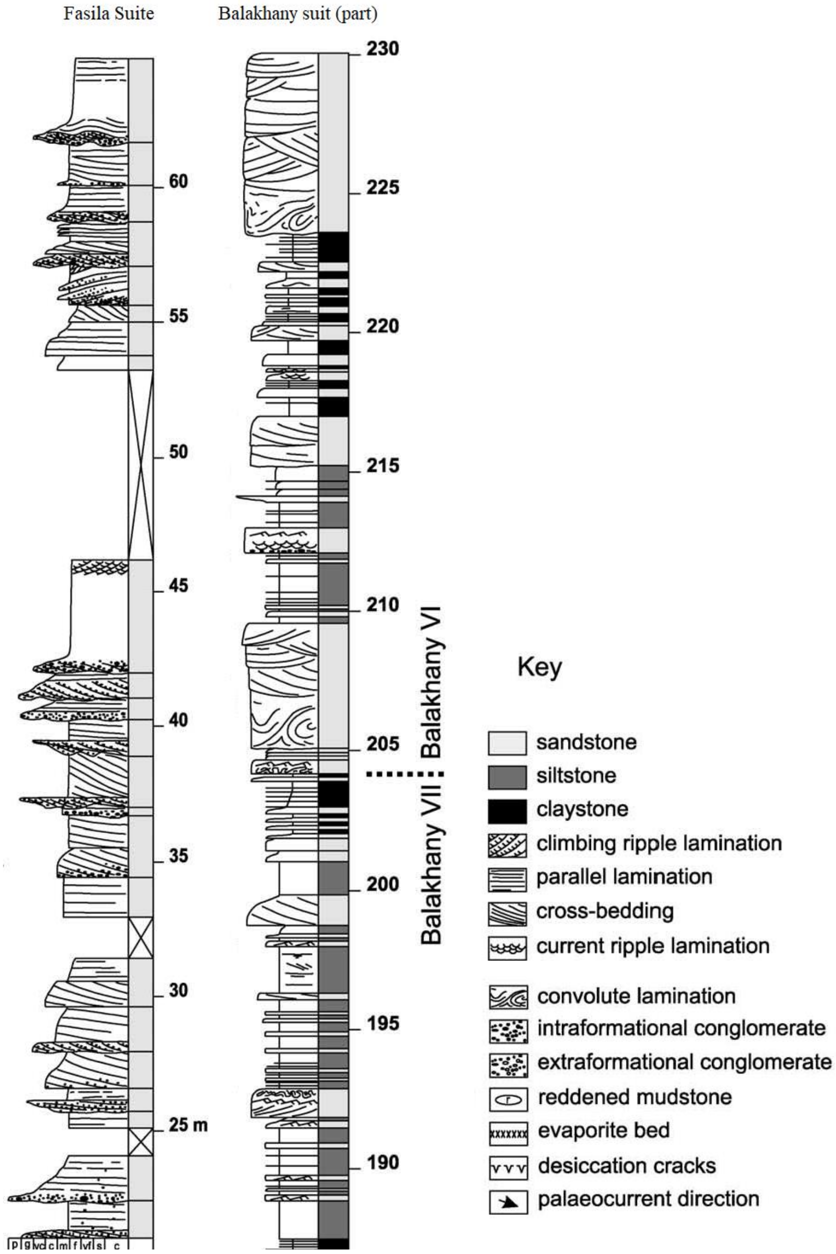


Fig. 4 Example of representative sedimentary logs of the Fasila Suite, and Balakhany subsuites from Kirmaky Valley (Hinds et al., 2004)

The highest quality reservoirs are found in the lower section of the upper Productive Series (Fasila and Balakhany suites) and are comprised of highly amalgamated, low sinuosity braided fluvial deposits with fine- to medium-grained sandstone. The Fasila Suite and Balakhany subunits X and VIII are the greatest places to find these facies. The lower net to gross subunits of the Balakhany Suite, especially subunit VI, and the top section of subunit VIII include potential reservoirs. The braided fluvial sandstones of these subunits are medium-to fine-grained, low sinuosity, and show reduced amalgamation, resulting in enhanced internal variability, with laterally continuous floodplain and channel abandonment facies establishing vertical and lateral barriers, respectively. The Sabunchi Suite also includes reservoir sandstone. However, these isolated fluvial sandstones are expected to have a minimal connection (Hinds et al., 2004).

The Fasila Suite is also one of the most important reservoir periods in the South Caspian Basin's Azerbaijan region. The Fasila Suite's basal contact is not extensively incised into the overlying mudstone-rich Post-Kirmaky Clay Suite, with a maximum erosive relief of only 5 m (Reynolds et al, 1998). Overlying the basal contact is a thin layer of poorly sorted, coarse sand- to granule-grade conglomeratic sandstone. (Fig 4) Trough cross-bedded conglomeratic sandstone-filled channel units amalgamate to a thickness of roughly 5 m when erosive relief is at its highest. The conglomerate is made up of lithic, igneous, and carbonate clasts that are sub-rounded to sub-angular (Hinds et al., 2004). Cenozoic and Mesozoic units exposed in the Greater Caucasus resemble limestone clasts, which is consistent with heavy mineral evidence suggesting a rise in the component of Greater Caucasus and in the Productive Series at the Fasila Suite's base (Morton et al., 2003).

From base to top, the Balakhany Suite is more than 300 m thick (Fig. 4). It is subdivided into six sub-units, as stated before. Balakhany Suite is one of the most productive part of Productive Series.

5. Origin of clay minerals

Clay minerals belong to the phyllosilicate family. Clays may contain additional cations, such as alkali, alkaline earth, and transition metals, in addition to aluminum and silicon. Clay minerals have a sheet-like structure in which the building blocks are either tetrahedra or octahedra that are connected into layers by sharing oxygen between adjacent tetrahedra or octahedra. The tetrahedra are formed by the tight packing of four O, with a Si^{4+} or, an Al^{3+} filling the space between them.

The octahedra are formed by the tight packing of six anions, the majority of which are oxygen ions but may also include some hydroxyl (OH) ions. The Si and Al ions fill the space between the oxygen octahedra and tetrahedra. Other cations, including iron, calcium, magnesium, and potassium, are necessary for the clay structure to guarantee charge balance. Layers of tens to thousands of nanometres separate tetrahedral and octahedral sheets from each other. The sorts of ions that occupy the octahedral positions in clay minerals can be categorized. The clay minerals are considered to be dioctahedral if the cations are trivalent (Al, Fe^{3+}) since only two ions are required to give six positive charges. The cations are said to be trioctahedral if they are divalent (Mg, Fe^{2+}) since three ions are required to provide six positive charges. Clay minerals rich in Mg and Fe^{2+} are generally trioctahedral, whereas Al- and Fe^{3+} rich clay minerals are dioctahedral.

Clays are a complex family of minerals that form by a wide range of processes, such as weathering of clay and non-clay minerals and rocks; erosion, transportation, and deposition of primary rock; hydrothermal alteration of minerals; diagenesis of sediments (Galán & Ferrell, 2013). The formation of clay minerals is also highly dependent on pressure and temperature conditions, as well as rock conditions.

Clay minerals have been difficult to analyze in the past, despite their great importance in fundamental geological research and the oil industry. For many years, standard clay mineral characterization methods such as XRD (X-ray Diffraction), petrographic microscope, XRF (X-ray Fluorescence), and SEM (Scanning Electron Microscopy) have been widely applied in conventional siliciclastic and carbonate reservoirs. X-ray diffraction (XRD) is used to determine the composition of rock minerals, as well as the kind and quantity of clay minerals. The reservoir mineralogy composition, pore types, authigenic clays, and cements may all be identified using a petrographic microscope. The mineral composition, morphology, distribution, and paragenesis of clays all may be studied using scanning electron microscopy (SEM). Because SEM has a broad depth of focus, it may provide a three-dimensional picture that can be used to study the structure of a material. It will help in the understanding of clay mineralogy and its impact on porosity, permeability, and other reservoir properties.

Before the usage of the scanning electron microscope (SEM), it was difficult to differentiate between authigenic and detrital clays (Worden & Burley, 2009). All clay minerals were widely assumed to be detrital in origin (Galán & Ferrell, 2013). Nowadays, roughly 90 % of the worldwide clay minerals are of detrital origin.

Processes that mainly occur during the genesis of detrital clay minerals are a breakdown of parental rocks (primary), erosion, and weathering. The primary sand is made up of a variety of minerals that developed under a variety of circumstances (temperature, pressure, oxidation state, and water composition) during deposition. Many grains in newly deposited sand have become unstable as a result of weathering, erosion, and transportation. As a result, the detrital mineral assemblage may be intrinsically unstable, leading it to react with the surrounding water during eodiagenesis. Detrital clays contain a history of weathering conditions in the surrounding region, whereas authigenic clays give insight into the geochemical environment. It has been determined that the initial depositional composition, i.e., the mineralogy of parent components in the original sediment, controls the clay minerals present in sandstones (both pore-filling and grain-coating) (Worden & Morad 2003). As a result, analyzing detrital mineral distribution patterns (clay and framework grains) in present sedimentary environments will help predict the spatial distribution of authigenic clay minerals like chlorite in deeply buried sandstones (Worden & Morad 2003).

Weathering processes in the source area, which are controlled by prevailing climatic conditions, have a big influence on the composition of detrital clay mineral assemblages in sediments (Chamley, 1989; Singer, 1984). Weathering may be divided into two main categories: physical and chemical. They differentiate by mechanical impact, chemical alteration, and temperature variations. Physical weathering occurs mostly in dry climates, resulting in the fragmentation and disintegration of rocks into their components without chemical alterations. Chemical weathering occurs when the climate is humid, and it results in a chemical change in the rocks. Clay minerals formation through the physical and chemical decay at 5 C<T<25 C lead to the transformation of the initial mineral (rock) to the clay mineral. Several factors that affect weathering reactions include temperature, humidity, primary rock type, presence of organic matter (Galán & Ferrell, 2013). Water attack, or hydrolysis, is the predominant chemical weathering process under normal pH circumstances (Fagel, 2007).

Clays can also be inherited from source locations and transferred to the deposition location with little mineral change (Galán & Ferrell, 2013). The initial phase in the sedimentary cycle of clay mineral deposits is the removal of sediment, soil, and rock particles by wind, water, and glaciers. The cohesiveness of the materials, their particle size distribution and aggregate structure, surface roughness, and climatic factors influencing the speed and duration of the erosive agents all impact the rate and degree of erosion by water and wind.

The diagenesis stage of the clay mineral cycle begins, when sediments are buried and pressure/temperature rise (Worden & Morad, 2003). Diagenesis includes a broad spectrum of post-depositional changes to sediments. It ranges from oxidation and weathering; compaction and lithification during burial to low-temperature metamorphism. Diagenesis is differentiated from metamorphism by a variety of characteristics, such as mineral and thermal history, although roughly a temperature transition of 180–250°C is separating the two regimes (Worden & Burley, 2009). Depositional facies, sandstone detrital composition, and climatic circumstances all have a role in the production of diagenetic clay minerals in sands at near-surface conditions and during shallow burial. All activities that occur at or near the sediment surface, where the geochemistry of the interstitial fluids is mostly influenced by the depositional environment, are termed eodiagenesis (Worden & Morad, 2003). Eodiagenesis may also be characterized in terms of temperature and depth, with a maximum temperature of 70°C, which is roughly comparable to a 2-kilometer burial. The main eogenetic clay minerals are kaolinite, di- and trioctahedral smectite, illite-smectite mixed-layer clays (I/S), glauconite, berthierine, and magnesium-clay minerals (palygorskite), which are originally formed by: pore water precipitation; replacement of previous detrital or diagenetic clay minerals; and framework sand grain replacement. Illite and chlorite do not form in eogenetic environments, therefore they are depositional rather than diagenetic in origin when found in sediments that have not undergone deep-burial diagenesis (Wilson, 1999). Mesodiagenesis is the term used to describe all diagenetic processes that occur after eodiagenesis and up to the early phases of low-grade metamorphism. In many situations, this comprises sediments deposited to depths of 200 to 250°C equivalent temperatures (Worden & Morad, 2003).

The influence of clay mineral diagenesis studies on oil and gas exploration success was predicated on the conclusion that there is a ‘Golden Zone' of reservoirs that fall within the 60–120 C depth window where smectite illitization occurs (Galán & Ferrell, 2013).

Authigenesis is a minor process that takes place in less than 10% of clay minerals, although it may be very important locally (Fagel, 2007). The authigenic clay minerals have been recognized as magnesium silicate minerals, e.g. kerolite, palygorskite, and sepiolite. The authigenic clay minerals can also consist of corrensite, dioctahedral smectite minerals, various mixed-layer minerals, along illite formed by illitization processes (Griffiths et al., 2018). The most often identified authigenic clays in sandstones are kaolinite and dickite, which are coarse enough to be visible in thin sections (Wilson & Pittman, 1977). Authigenic clay minerals form after diagenesis and hydrothermal alteration, as stated before. Crystalline tendencies are common in authentic clays. This is one of the earliest and most extensively used criteria for identifying authigenic clays, and it is thought to be quite accurate. The clay flakes' delicate nature prevents them from being transported for long periods. These criteria apply to authigenic chlorite, kaolinite, and dickite in particular. Authigenic clays can achieve high purity levels. This might be reflected in their chemical composition, color and texture homogeneity, and transparency. These characteristics may be seen in a lot of authigenic clays. Minor impurities such as finely crystalline diagenetic pyrite or hydroxides, on the other hand, may obscure this property and prevent it from being used. Degradation during erosion and transit, as well as mixing with nonclay impurities during deposition, are all factors that contribute to the impure character of detrital clays. The size of the authigenic clay flakes in many sandstones may be too tiny for a full examination of this characteristic (Wilson & Pittman, 1977).

Authigenic clay minerals may be monomineralic. This is because such clays are only formed within a small range of subsurface physical and chemical conditions. Detrital clays are usually mixed with two or more clays since they come from a wide range of rock types and soils. Although few authigenic clays are completely monomineralic, many of them include only traces of other clays. Many sandstones, on the other hand, include two authigenic clays, and sandstones with three authigenic clays have also been discovered (Wilson & Pittman, 1977).

Smectite, illite, kaolinite, chlorite, and mixed-layer minerals are the most attractive ones because of their importance to petroleum engineers and geologists (Ruhovets & Fertl, 1982).

Smectite

Smectite is a two-layer mineral with different amounts of the exchangeable cations Na and/or Ca and also some minor elements (e.g., Co, Cu, Ni) in the interlayer and one or two layers of water. Smectite's origin in sediment basins is occasionally a source of debate. Smectite is weathering product of mafic rock (igneous rock/silicate mineral rich in magnesium iron). Smectite is finer-grained (lower particle size) than the other clay types, with particle sizes ranging from 0.9 m to less than 0.1 m on average, with a mean of around 0.4 m. Both eogenetic and detrital origins are possible for smectitic clay minerals in siliciclastic rocks. Formation of smectite frequently occurs under the following conditions: poor drainage of the soil, base-rich initial rocks, and high pH (Worden & Morad, 2003). Detrital smectites, on the other hand, are formed mostly by the hydrolysis of feldspars and are sourced from nearby land. Well-crystalline smectites are usually found in subtropical climates with poorly drained landscapes, with annual precipitation ranging from 500 to 800 mm (Thiry, 2000). Detrital smectite is a kind of smectite that grows on floodplains. Smectite production is only a minor process in a dry climate (Thiry, 2000). Authigenic smectites can be produced from hydrothermal activity or diagenetic processes, or they can be the result of an alteration of basaltic volcanic glass and volcanic rock fragments (Chamley, 1989).

It’s believed that when smectite group minerals are found in petroleum reservoirs, they play a key role in hydrocarbon migration (Worden & Morad, 2003). Smectite may be found in the shallow level of reservoir rocks, but when the temperature rises, it converts into other clay minerals. In general, dioctahedral smectites change to illite, whereas trioctahedral smectites transform to chlorite, removing interlayer water molecules in both cases. The released water raises the pore fluid pressure, which might cause the hydrocarbon migration (Worden & Burley, 2009).

Illite

Illite comprises a combination of two tetrahedral sheets and one intercalated octahedral sheet (layer type 2/1). Illite is a widespread mineral in many types of rocks and is considered the commonest clay mineral; predominant in marine clays and shales. Detrital illite is mostly formed by the weathering of felsic silicate-rich crystalline basement rocks in a dry climate (Weaver, 1989). Detrital illite is mainly resistant to chemical weathering, although dioctahedral illite (muscovite) is significantly more resistant than trioctahedral illite (biotite) (Fagel, 2007). Illite is formed through the transformation of smectite into illite by illitization of illite-smectite mixed-layer clay minerals (Meunier and Velde, 2004).

Chlorite

Chlorite has three sheets, two tetrahedral and one octahedral, but the interlayer area is occupied by a hydroxide layer (layer type 2/1/1). Although most chlorites in sedimentary settings are trioctahedral, with bivalent cations such as Fe, Mg, Mn, or, more rarely, monovalent cations (Li, Ni) filling 3/3 of the octahedral sites. Due to various potential replacements in both the tetrahedral and/or octahedral layers and the interlayer, their chemical composition is complicated and variable. Basalt-seawater contact produces authigenic chlorite at temperatures of 475-600°C (Aghayev, 2006). Additionally, authigenic chlorite might be the consequence of volcanic material being altered (Weaver, 1989). Chlorite is weathering product of mafic silicates. Detrital chlorite mainly forms by physical weathering of plutonic and metamorphic rocks such as schist and gneiss by hydrolysis (Chamley, 1989; Aghayev, 2006).

Kaolinite

One tetrahedral layer and one octahedral layer (layer type 1/1) combine to form kaolinite. It's a dioctahedral mineral with a trivalent cation (Al or maybe Fe3+) filling two-thirds of the octahedral sites. These white, powdery minerals are weathering products of feldspars (Galán & Ferrell, 2013). Kaolinite is formed in continental sediments by the impact of low-pH ground fluids on detrital aluminosilicate minerals including feldspars, mica, rock fragments, mud intraclasts, and heavy minerals under humid climatic circumstances (Worden & Morad, 2003). The low-temperature form of kaolin is kaolinite, whereas the high-temperature forms are dickite and nacrite. Authigenic kaolinite develops during smectite diagenesis (Chamley, 1989). Hydrolysis mechanisms enhance the production of detrital kaolinite from K-feldspar, plagioclase, and biotite in areas with high rainfall, a warm, humid environment, and well-drained topographies (Aghayev, 2006). The quantity of unstable detrital silicates, hydraulic conductivity, precipitation, and rate of fluid movement in the sand body all impact the amount and distribution pattern of kaolinite (Wilson et al., 2014). Permeable sediments, such as channel sand deposits, are the most susceptible to eogenetic grain dissolution. Humidity increases the availability of meteoric fluids, which leads to the formation of eogenetic kaolinite. Petroleum geologists prefer reservoir rocks with kaolinite as the major clay mineral in their cement, partially because kaolinite swells less than other clays (Wilson et al., 2014).

Mixed-layer clay minerals

Mixed layers are created by stacking two or more layer types in a regular or irregular pattern. The interstratification, or simply mixing can be ordered (regular), segregated regular, or random (irregular) (Reynolds, 1980). In sedimentary environments, we do not observe all possible combinations of clay minerals. The common type of mixed-layer clays includes kaolinite-smectite, illite-smectite, illite-vermiculite, chlorite-vermiculite, chlorite-smectite types.

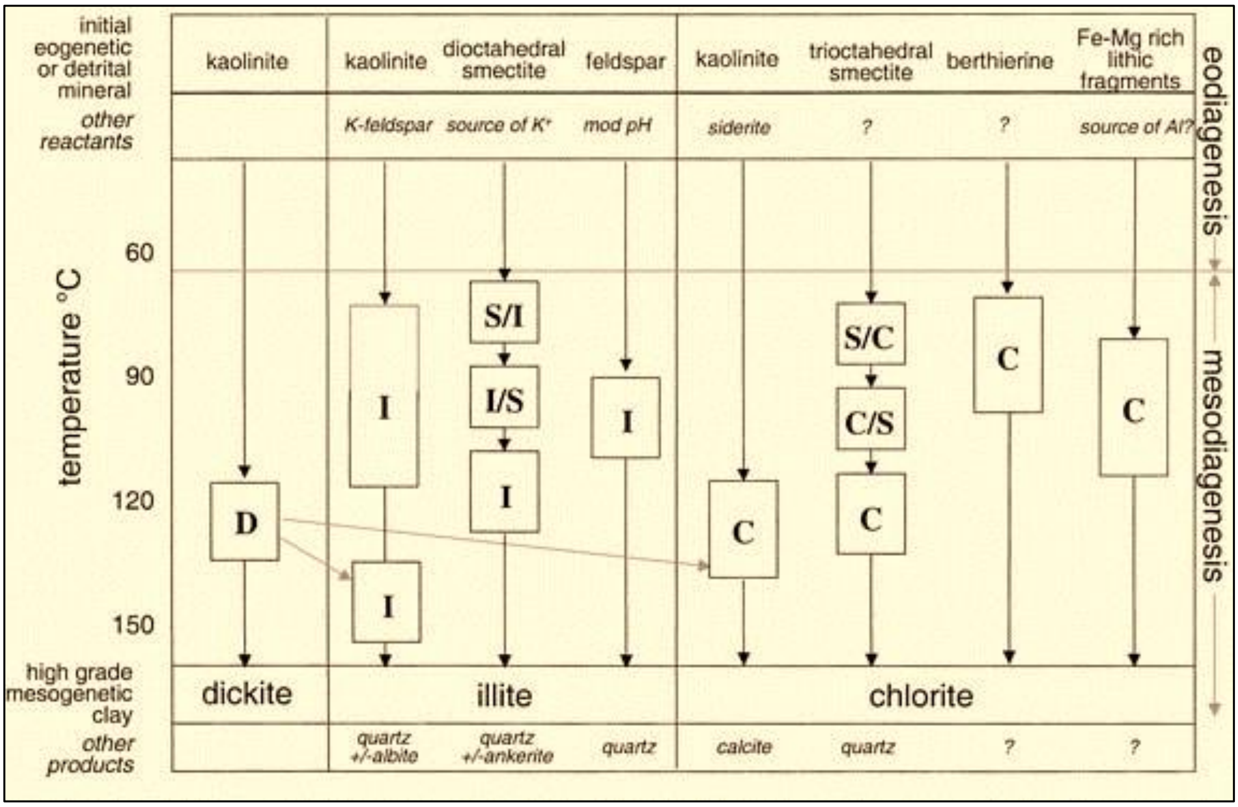


Fig. 5 Typical mesogenetic processes in sandstones for clay minerals (Worden & Morad, 2003). Dickite, smectite, illite, and chlorite are the minerals represented by the letters D, S, I, and C, respectively.

For example, authigenic dioctahedral smectite develops to illite after burying and heating, moving through interlayered forms. The composition of the dioctahedral smectite varies, but it usually has a low Al/Si ratio and contains Ca, Fe, and Mg. There are two ways that dioctahedral smectite might become illite. The first conserve silica and so requires a supply of aluminum to convert into illite. The second is to save aluminum while producing too much silica (probably as quartz cement). Only a few examples of pure dioctahedral smectite in sandstones have been found (most contain at least some illite).

In Fig. 5 we can observe most common mesogenetic processes in sandstone for clay minerals. The most abundant layer type is given first in mixed-layer clay minerals: S/I stands for mixed-layer smectite–illite with smectite as the dominant mineral; I/S stands for the same mineral mixture with illite as the dominant mineral. Interlayered smectite–chlorite follows the same naming rules. Dickite, illite, and chlorite clay minerals form in sandstones as a result of high-grade diagenesis. During mesodiagenesis, kaolinite can be supplanted to produce dickite, illite, or even chlorite. During mesodiagenesis, illite can be formed in at least three ways. It does not develop during eodiagenesis, but can be a detrital clay. Chlorite is formed by at least four different routes and also is unlikely to occur during eodiagenesis (Worden & Morad, 2003).

5.1 Chemistry of clay minerals

The clay minerals have a fine-grained structure. They build-up of the tetrahedrally (Si, Al, Fe^{3+}) and octahedrally (Al, Fe^{3+}, Mg) coordinated cations structured to sheets or chains. All of them are hydrous. Silica sheets and brucite or gibbsite sheets are the main structural elements of layer silicates. The former is made up of SiO_2 tetrahedra that are joined in a hexagonal network at three corners in the same plane. The tetrahedral sheet is the name for this unit. Between two planes of hydroxyl ions in the brucite or gibbsite sheet there is a plane of magnesium or aluminum ions that is octahedrally coordinated by the hydroxyls. This unit is called the octahedral sheet. In the octahedral sheet the oxygens at the tips of the tetrahedra extend into a plane of hydroxyls, replacing two-thirds of the hydroxyls in the octahedral sheet. A layer is formed by the combination of sheets.

The primary subdivision of layer lattice silicates is based on the kind of tetrahedral and octahedral sheet combinations. Additional categorization is based on:

(1) whether the octahedral sheet includes two cations per half unit cell (dioctahedral) as in gibbsite or three cations per half unit cell (trioctahedral) as in brucite;

(2) the manner in which the tetrahedral-octahedral units are stacked upon each other;

(3) the quantity and kind of isomorphous cation substitution.

One tetrahedral sheet and one octahedral sheet make up the 1: 1 clay-mineral type. The kaolinite (dioctahedral) and serpentine (trioctahedral) groups formed this two-sheet type. The kaolinite is pure hydrous aluminum silicates.

Serpentines are two-sheet minerals with a trioctahedral structure. This subgroup includes serpentine minerals (the most prevalent of which are chrysotile and antigorite), which are made up of a tetrahedral sheet and an octahedral sheet containing magnesium and very small amount of aluminum. The composition of the other minerals in this subgroup varies significantly. In typical sediments, serpentines are generally found mixed with kaolinite and/or chlorite and are difficult to distinguish. Two silica tetrahedral sheets are layered between an octahedral sheet in the three-sheet or 2:l layer lattice silicates. Two-thirds of the octahedrally coordinated hydroxyls are substituted by the oxygens at the tips of the tetrahedra, which point towards the central octahedral sheet. The mica and smectite families, which are by far the most widespread clay minerals, are among the 2: 1 clay minerals. Talc, a hydrous magnesium silicate; pyrophyllite, a hydrous aluminum silicate; and minnesotaite, a hydrous iron silicate, are the pure end members of this group. The micas' 2:1 structural unit is similar to that of talc, but there is a plane of large cations between the 2:1 units. They called interlayer cations. The most frequent is potassium, but sodium and calcium can also be found. These interlayer cations connect nearby 2:1 units by fitting within the hexagonal ring produced by the tetrahedral oxygen ions. The interlayer cations balance the charge by substituting lower-charge cations for higher-charge cations in the tetrahedral and/or octahedral sheets. The basic 2:1 units can be layered in a number of ways (polytypes): 2M (two-layer monoclinic), 1M (one-layer monoclinic), 1Md (disordered one-layer monoclinic), and 3T (three-layer trigonal). By far the most prevalent are the first three. Muscovite is usually classified as type 2M, phlogopite as type 1M, and mixed-layer clays as type 1Md.

Mica species are classified as dioctahedral (muscovite type) or trioctahedral (biotite type). Furter characterisation includes the number of silicon ions in the tetrahedral configuration: t etrasilicic, trisilicic, disilicic, and monosilicic. Silicon is replaced by aluminum or, less typically, ferric iron. The micas are also divided into groups based on the variety of cations and combinations of cations found in the octahedral sheet. The only two elements that occur alone in the octahedral sheets are aluminum (muscovite) and magnesium (phlogopite). The octahedral sheets of most micas include two or more cations; aluminum, magnesium, and iron are found in various combinations in the octahedral sheet. In variable concentrations, Mn, V, Cr, Li, Ti, and a range of other cations also can be found. The 2:1 layer has a net negative charge that is met by the interlayer cations when a lower charge cation replaces a higher charge cation in both the octahedral (e.g., Mg replacing $A1^{3+}$) and tetrahedral (e.g., $A1^{3+}$ replacing Si^{4+}) sheets. Mica names list have been developed from the study of coarse-grained minerals (Foster, 1956; Garshaw and Roy, 1961)

The illite family includes fine-grained micas. The dioctahedral illites dominate the trioctahedral illites. The most common illite mineral is dioctahedral, with about half as much aluminum as muscovite substituting for silicon in the tetrahedral sheet. Aluminum makes up around three-quarters of the octahedral cations; tiny levels of ferric iron may be found, and only one-eighth of the cations are divalent (magnesium and ferrous iron). Glauconite and celadonite minerals are dioctahedral iron illites. Iron illite layers, like aluminum illites, are frequently interlayered with montmorillonite-like layers. More than half of the octahedral sites in glauconites are filled with iron, with ferric iron being the most prevalent. The tetrahedral sheet's aluminum content is generally lower than that of the aluminum illites, while the octahedral sheet's magnesium concentration is higher. Compared to glauconite, celadonite has more octahedral Mg and less tetrahedral Al. As pure minerals concentrates, trioctahedral illites are uncommon. The clay-sized minerals are generally mixed-layer biotite-vermiculite because the interlayer cations are relatively easily leached from biotite (expanded biotite). molecules, which are characterized by loosely attached cations. The width of the interlayer may be changed in both directions. At temperatures between 120°C and 200°C, the interlayer water may be driven off. The most frequent naturally occurring interlayer cations include sodium, calcium, hydrogen, magnesium, iron, and aluminum.

By far the most common is the dioctahedral subgroup. Dioctahedral vermiculite refers to a group of minerals that have been identified as having been formed by leaching potassium from illite or muscovite. Dioctahedral vermiculite is a group of minerals that are known to have been formed by leaching potassium from illite or muscovite. Trioctahedral expanded clays exist in a wide range of sizes, despite their rarity in sediments. Hectorite, which has magnesium and lithium in the octahedral sheet, and saponite, which has magnesium in the octahedral sheet and some aluminum substitution in the tetrahedral sheet, are the most abundant ones.

Vermiculites are trioctahedral expanded 2:1 minerals. Most expanded clays have finer grains and worse crystal organization than these minerals. Interlayer cations may be removed from any non-expanded 2:1 and 2:1:1 layer silicates. Water and organic molecules can then pass across these layers, resulting in extended layer minerals.

Chlorite can be found as a clay-sized mineral. The majority of them have a 2:1 talc layer and a brucite sheet. Although a few dioctahedral chlorites have been discovered, the majority of chlorites are trioctahedral. Some chlorites feature sheets are both dioctahedral and trioctahedral. The chlorites have a wide variety of compositions because substitution can occur in both the 2:1 layers and in the brucite sheet.

Mixed-layer clays are a form of clay that consists of interstratified units of various chemical composition rather than being pure mineral types. Mixed-layer illite-montmorillonite is by far the most common mixed-layer clay (approximately 90%). The two layers can be found in any ratio between 9:1 and 1:9. Those with a 9:1 or even 8:2 ratio are known as illites or glauconites, while those with ratios of 1:9 and 2:8 are known as montmorillonite. Chlorite-montmorillonite, biotite-vermiculite, chlorite-vermiculite, illite-chloritemontmorillonite, talc-saponite, and serpentine-chlorite are some of the other random mixed-layer clays. One of the layers is usually enlarged, while the other is nonexpanded. Sepiolite and attapulgite are type of clay minerals with a chain structure. The former has five octahedral positions, whereas the latter has either eight or nine octahedral positions. Both have a little amount of tetrahedral substitution. Sepiolite's octahedral positions are mostly filled with Mg, while attapulgite's are about half Mg and half Al.

5.2 Distribution of clay minerals in the Pliocene Productive Series sediments from the western South Caspian Basin

It is necessary to establish the source region of clay minerals before analyzing the influence of clay minerals on reservoir quality. Several investigations have been conducted on the origin and distribution of clay minerals found in Productive Series (PS) sediments from the South Caspian Basin.

There have been a few investigations on the distribution of clay minerals in PS sediments from the South Caspian Basin. Kosovsgoy's research was the first (1954). Pashaly and Kheirov conducted further research on PS sediment samples from the Absheron Peninsula, Absheron Archipelago, and Baku Archipelago (1979). The purpose of these investigations was to compare the PS sediments to the Red Suite, or Pliocene sediments from the Caspian Sea's Turkmenistan region. The result of the study showed that the amount of illite in the PS is increasing from the Baku Archipelago to Absheron Peninsula. The quantity of illite in the Productive Series from the Baku Archipelago is only 40-45 %, but it is moreover 50 % on the Absheron Peninsula. Later research showed the clay mineral distribution in specific locations of the South Caspian Basin's western flank (Turovskiy et al., 1981).

Turovskiy et al. (1981) discovered that near the modern Volga River and the modern Samur River, relatively high amounts of illite and relatively low amounts of smectite can be found, whereas, near the modern Kura river region, relatively low amounts of illite and relatively high amounts of smectite can be found. As a result, these two clay minerals appear to be good provenance indicators.

Later studies of Buryakovsky et al (1995) showed that most of the clay minerals in the South Caspian Basin reservoirs belong to the smectite and illite groups. Kaolinite content varies from 15 to 20%, chlorite from 5 to 10%, and mixed-layer minerals up to 5% (Buryakovsky et al., 1995).

Abdullayev and Leroy (2016) studied clay mineral composition and distribution in Pliocene Productive Series sediment from western South Caspian Basin (Fig. 6), which also identifies possible source sites for the various research zones. There are three sediment sources for the clay mineral assemblages of the South Caspian Basin: Russian Platform, Greater Caucasus, and Lesser Caucasus (Abdullayev & Leroy, 2016). Different sediment source regions for the Lower and Upper Divisions may be differentiated using clay mineral assemblages from the Productive Series. Various research locations of the Lower Division sediments contain the same clay mineral composition, indicating a probable unique sediment source in the Russian Platform. The Palaeo-Volga River system drained the Russian Platform. (Reynolds, Mortan; Abdullayev & Leroy, 2016). Different clay mineral compositions in Upper Division sediments from various research locations indicate that the clay minerals are generated from different sources. The Upper Division clay mineral assemblages of the Absheron Peninsula have a high illite concentration and a low smectite content. The Russian Platform, which was drained by the Palaeo-Volga River, might be a source for Upper Division sediments from the Absheron Peninsula. The Upper Division has a mixture of illite and smectite, and more chlorite than kaolinite. The clay mineral assemblages from the South Absheron Offshore Zone point to the Greater Caucasus, which was drained by the Palaeo-Samur River, as a possible source for the Upper Division deposits. The main source region for PS sediment from the Absheron Peninsula was the Russian Platform, which was mostly generated from the Palaeo-Volga River (Abdullayev & Leroy, 2016).

The mineralogical composition of the source rocks in the surroundings has a great influence on the clay mineral assemblages in the PS. Distinct clay mineral assemblages in PS sediments allow different sources areas to be distinguished.

The analyses of Abdullayev and Leroy (2016), Seidov & V., (1968), and Turovskiy et al (1981) clearly demonstrated that the Productive Series (PS) clay minerals from Absheron Peninsula, Absheron Archipelago, South Absheron Offshore Zone, and even Baku Archipelago are of detrital origin. Clay minerals from the Pleistocene/Holocene of the southern part of the Caspian Sea have significant Zr, Rb, and Th concentrations, confirming their detrital origin.

Abdullayev and Leroy (2017) also studied clay minerals as palaeoclimatic markers in the PS, western Southern Caspian Basin. Because the clay minerals of the PS from the Absheron Peninsula and South Absheron Offshore Zone are mostly detrital in origin, alterations in clay mineral assemblages are a function of weathering conditions and therefore are influenced by the climate in the hinterland. They stated that because changes in clay mineralogy in Absheron Peninsula and South Absheron Offshore Zone are assumed to be driven by climatic changes within the corresponding source area, the clay mineral assemblages of the PS sediment may help to reconstruct palaeoclimatic conditions. They used the Pliocene Productive Series clay mineral composition and total organic carbon (TOC) from the western

South Caspian Basin to recreate palaeoclimate on the surrounding land, which is still a data-poor area. Variations in smectite and illite content in the Lower Division of the Productive Series show that on the Russian Platform, two distinct climatic regimes alternated. Arid climatic conditions are indicated by a high amount of illite paired with a low amount of smectite and a low level of TOC. On the Russian Platform, however, a large amount of smectite and TOC combined with a low amount of illite suggests a humid climate. The Absheron Peninsula's Upper Division of the Productive Series is characterized by a large proportion of illite, which implies arid climatic conditions. Changing smectite and illite compositions in the Upper Division of the Productive Series in the South Absheron Offshore Zone indicate a climate in the Greater Caucasus that alternates between aridity and humidity.

The palaeoclimate reconstruction based on clay mineral compositions corresponds with the concepts of a highly changeable climate throughout the Early Pliocene proposed by Hinds et al. (2004) and Abreu and Nummedal (2007). Warming in the Early Pliocene was related to humid conditions on the Russian Platform and high water levels in the Caspian Sea. The cooling in the Middle-Late Pliocene, on the other hand, represented the dry environment of the Russian Platform, when the Caspian Sea water level dropped (Frakes et al., 1992).

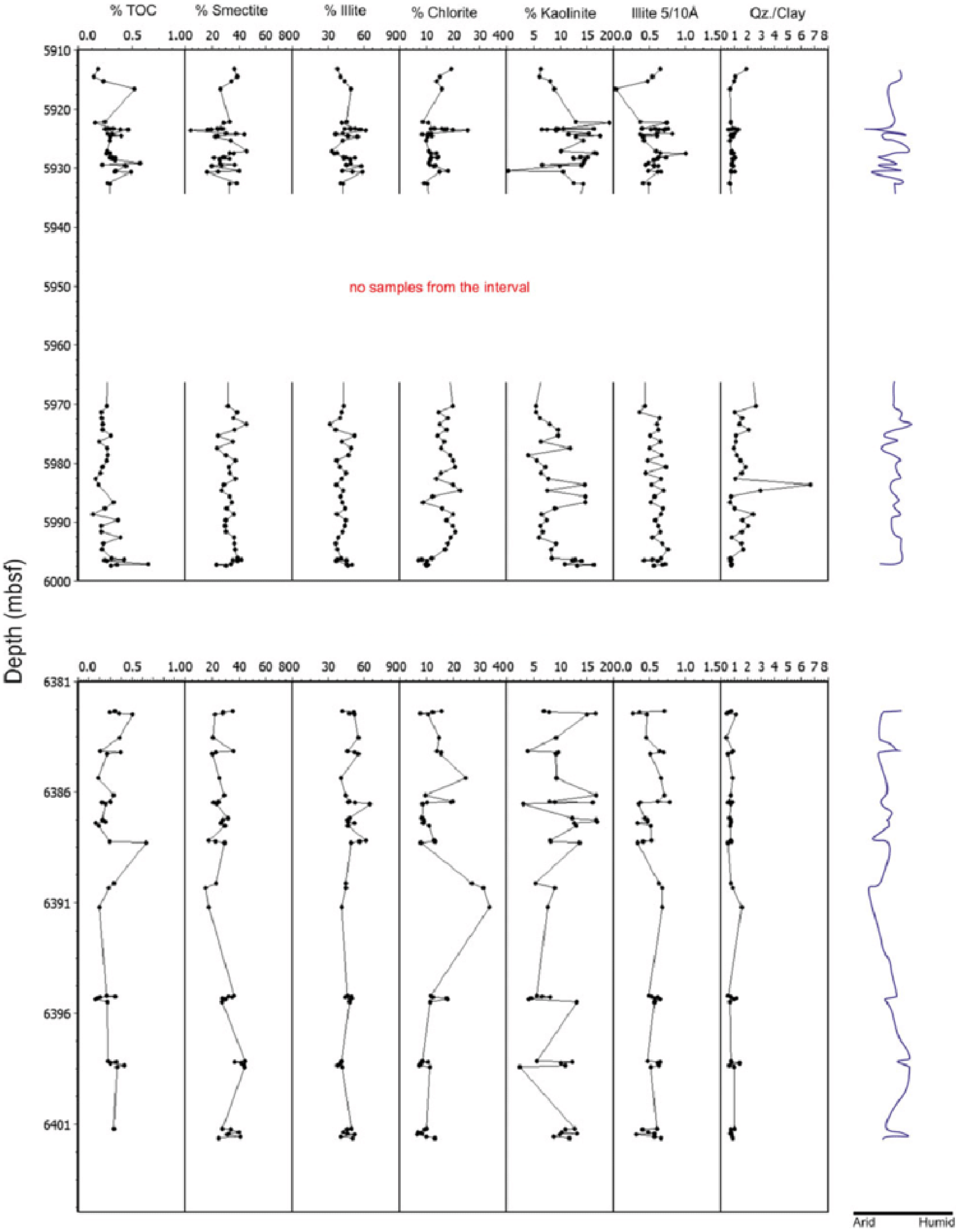


Fig. 4 Smectite, illite, chlorite, kaolinite, and normalized quartz/clay ratio in the <2 m fractions (%) of the Fasila Suite and Balakhany VIII sub-suite of the Productive Series from Shah-Deniz, South Absheron Offshore Zone. (Abdullayev & Leroy, 2016)

6. Reservoir quality

The hydrocarbon storage capacity and deliverability of a reservoir determine its quality. The effective porosity and the reservoir size determine the hydrocarbon storage capacity, whereas the permeability determines the deliverability. Petroleum reservoir porosity and permeability (also known as reservoir quality) are critical inputs for effective oil and gas resource exploration and exploitation. The economic viability of a petroleum accumulation is strongly influenced by porosity and permeability (Blackbourn 2012). In order to reduce cost and increase return on investment, they should be measured from basin access and exploration through appraisal and field development, as well as secondary and tertiary recovery. As a result, with the exploration and production of petroleum in increasingly difficult conditions and from less conventional reservoirs, the subject of reservoir quality prediction is becoming highly significant.

The storage capacity of a reservoir is determined by its porosity. Porosity is the ratio of void space (also known as pore volume) to bulk volume, and it's expressed as a fraction or a percentage. Almost all hydrocarbon reserves are made up of sedimentary rocks, with sandstones porosity values ranging from 10 to 40%. The volume proportion of interconnected pores in a rock is known as effective porosity. Grain size, packing, form, sorting, and the quantity of intergranular matrix and cement all affect primary porosity. Porosity is independent of grain size theoretically. Changes in grain size, on the other hand, have an impact on grain shape and sorting. Changes in grain size have an indirect effect on porosity since these factors impact it directly. Graton and Fraser estimated the porosity of various packing arrangements of uniform spheres to study the theoretical effects of grain size and packing on porosity. Regardless of the value supplied to grain radius, the theoretical maximum porosity for a cubic packed rock is 47.6%. Other packing configurations' porosity values can be estimated. Due to the tighter packing arrangements associated with spherical grains, porosity reduces as sphericity rises. Porosity rises with sorting, according to several research.

The ability, or measurement of a rock's ability, to transmit fluids, typically measured in darcies or millidarcies. The term was basically defined by Henry Darcy, who showed that the common mathematics of heat transfer could be modified to adequately describe fluid flow in porous media. Formations that transmit fluids readily, such as sandstones, are described as permeable and tend to have many large, well-connected pores. Impermeable formations, such as shales and siltstones, tend to be finer grained or of a mixed grain size, with smaller, fewer, or less interconnected pores. Absolute permeability is the measurement of the permeability conducted when a single fluid, or phase, is present in the rock. Effective permeability is the ability to preferentially flow or transmit a particular fluid through a rock when other immiscible fluids are present in the reservoir (for example, effective permeability of gas in a gas-water reservoir). The relative saturations of the fluids as well as the nature of the reservoir affect the effective permeability. Relative permeability is the ratio of effective permeability of a particular fluid at a particular saturation to absolute permeability of that fluid at total saturation. If a single fluid is present in a rock, its relative permeability is 1.0. Calculation of relative permeability allows for comparison of the different abilities of fluids to flow in the presence of each other, since the presence of more than one fluid generally inhibits flow. The size, shape, and distribution of pore channels in the rock, the type and number of fluids present, the fluid flow rate, the length and cross-sectional area of the rock, and the pressure differential across the length of flow are all factors that influence permeability.

There is often a direct relationship between porosity and permeability. Greater porosity is usually associated by increased permeability, however the exact connection varies depending on the formation and rock type.

Even though measuring porosity and permeability using core analysis techniques or wireline logs using a combination of density, sonic, neutron, and NMR logs is absolutely essential for reservoir characterization, these methods do not directly reveal the controls on reservoir quality and thus do not allow for prediction away from the wellbore (Rider & Kennedy 2011). In order to determine the predominate controls on reservoir quality, it is necessary to define grain types and mineralogy, grain–grain contacts, intergranular volume (a proxy for the extent of compaction), matrix type and amount, cement mineralogy and morphology, and pore types, their genesis, and proportions. Quantifying the effective stress, temperature, and thermal history of a sedimentary rock, as well as the fluid composition under which it evolved from deposition to burial and uplift, is also critical for achieving a comprehensive knowledge and making accurate reservoir quality projections. Process-oriented diagenetic models that take into account these depositional and burial history characteristics have the potential to provide deeper insights into reservoir quality controls while also serving as powerful prediction tools, especially when combined with other disciplines like sedimentology, structural geology, geomodelling, and reservoir engineering.

Despite the significance of understanding controls on porosity and permeability, there is no clarity on a number of fundamental concerns. The origin of the sediment (provenance), depositional environment, weathering and climatic conditions in the hinterland and at the site of deposition, compaction, recrystallization and dissolution, authigenic mineral growth, petroleum charge, depth of burial, extent and rate of heating, fluid pressure and effective stress and structural deformation are all interdependent sedimentary and diagenetic factors that influence reservoir quality (Morad et al. 2012). Although several of these parameters are interconnected, they are usually considered independently, which makes reservoir quality prediction difficult. Further challenges occur as a result of several basic unsolved debates that impede the development of widely recognized reservoir quality prediction models and methodologies. For example, these include the impact of petroleum on mineral development, whether effective stress or temperature regulates pressure solution (chemical compaction).

The spectrum of analytical methods and approaches used for reservoir quality prediction in sandstones are almost entirely overlapping. Regardless of the host reservoir type, regular procedures including seismic interpretation, wireline logging, and core analysis are frequently used to assess reservoir quality. Sandstones require sedimentological core description to show rock type, lithofacies, sedimentary and tectonic features, and macroporosity.

There are a variety of methods for measuring reservoir quality, ranging from macroscopic to microscopic.

Macroscopic methods

Modern three-dimensional seismic data can help estimate reservoir quality away from well control. The seismic reflection amplitudes can be converted to acoustic impedance estimations with careful processing of seismic data. Because the acoustic impedance of a rock is affected by lithology, porosity, and fluid saturations, a relationship may be formed between seismic estimations of impedance and rock characteristics derived from logs or in the laboratory. Based on the information they contain, wireline logs may be divided into three categories: (1) lithology indicators, such as gamma ray, sonic, density, and neutron logs; (2) porosity logs, such as sonic, density, and neutron logs; and (3) fluid saturation logs, such as resistance logs.

Permeability can occasionally be derived from log responses or a mixture of log responses in addition to lithology, porosity, and fluid saturations. Permeability can frequently be determined from log responses or a mixture of log responses in addition to lithology, porosity, and fluid saturations. The spontaneous potential log is frequently employed as a qualitative indication of a formation's permeability. Drill stem testing (DST) or formation testing is another macroscopic approach for determining reservoir quality. After the well has been conditioned by closing the zone(s) of interest and permitting fluid production, a drill stem test is usually done. The fluids' hydrocarbon content is determined, and pressures and flow rates are monitored. The formation's productive capability is assessed by the types of fluid generated and the flow rates, and the permeability may be extrapolated from pressures monitored over time.

Mesoscopic methods

Core analysis measures on representative core samples can help estimate reservoir quality and heterogeneities more precisely. Porosities in core analysis are often calculated using one of three methods: fluid summation, resaturation, or Boyle's Law. Permeability is measured using one of two methods: steady-state or unsteady-state. The steady-state and unsteady-state methods may both be used to calculate liquid permeability. Capillary pressure may also be evaluated from core samples in the lab. Various procedures are applied to determine fluid saturations in the sample at different pressures, resulting in a saturation profile that describes the rock's irreducible water saturation and hydrocarbon pore volume.

Miscroscopic methods

Thin section analysis, petrographic image analysis, scanning electron microscopy, and X-ray diffraction are some of the microscopic techniques used to determine reservoir quality. The pore types and distribution, the level of reservoir enhancement or degradation due to diagenesis, and the effect of depositional textures on reservoir quality may all be assessed with the help of thin section analysis.

Scanning electron microscopy (SEM) with energy-dispersive X-ray is another microscopic way of determining reservoir quality. The SEM enables for high magnification and depth of field investigation of a reservoir rock, allowing the pore network and clay minerals within the pores to be seen. Energy-dispersive X-ray analysis is used to determine the mineralogy and gives an elemental analysis of the grains, cements, and clays discovered by the SEM. This type of investigation is critical for determining the risk of formation damage caused by the introduction of potentially reactive stimulation fluids. Cuttings, percussion sidewall cores, and unconsolidated core samples are appropriate for petrographic image analysis, which yields porosity and permeability values as well as capillary pressure curves for sandstone samples that are not suited for conventional core analysis. Using a research-grade petrographic microscope and an image analysis system, image analysis assesses essential two-dimensional geometrical properties of the pore network in thin section. From thin section images of undamaged areas of the sample, the system outputs a binary picture indicating porosity and rock composition. Pore area, diameter, perimeter, length, breadth, and aspect ratio may all be calculated and compared using this picture, as well as three-dimensional porosity, permeability, and capillary pressure data obtained from traditional core samples.

7. Impact of clay minerals on reservoir quality

Clay minerals have an essential role in generating and storing oil and gas in reservoir rocks. As stated before, the most significant characteristics of reservoir quality are porosity and permeability. Clay minerals are thought to be detrimental to sandstone reservoir quality because they can block pore throats by forming films, plates, and bridges on the grain surface, and some clay minerals enhance chemical compaction. (Galán & Ferrell, 2013)

Fundamentally, the diagenetic process, which includes mechanical compaction, an increase of quartz and K-feldspar, carbonate cementing, and clay mineralization, is the major source of porosity reduction. Illite and illite-smectite clays are the earliest cements formed during intermediate to deep burial diagenesis. During burying diagenesis, these early-formed clay films play an important role in decreasing reservoir porosity and permeability. Pore-filling illite, for example, is produced mostly at the expense of kaolinite. Illitic clays are most commonly found as pore-bridging clays, which decrease pore space and restrict fluid flow by lowering permeability. (Sun et al., 2019) Clay minerals, which have replaced rigid feldspar minerals, compact easily and may be compressed into pore throats between grains. This will also have a significant impact on the decrease of reservoir quality. Coarse granularity, high quartz content, and low clay content are all characteristics of high-quality reservoirs, as are extensive chlorite coatings that prevent quartz cementing at low temperatures. High-quality reservoirs generate more pores at higher temperatures, allowing growing space for quartz cements and resulting in the coexistence of chlorite coatings and quartz cements. Rather than chlorite coatings, lithological features determine the quality of high-quality reservoirs. By decreasing the size and connectedness of pore-throats, illite and I/S clays cause serious harm to reservoirs (Taylor et al., 2015).

Even though, as previously stated, the porosity and permeability of reservoirs reduce with increasing burial depth because of diagenetic processes, other diagenetic processes, such as fractures, cement removal or leaching of framework grains, preexisting types of cement and clay minerals, restricted compaction, and/or limited cementation, may increase porosity by generating secondary porosity. Secondary porosity is created from post-depositional processes, such as dissolution and fracturing. The pore spaces between grains generated during depositional processes like sedimentation and diagenesis are classified as primary porosity (Carcione et al., 2019). A large percentage of secondary porosity may be due to the dissolving of clay minerals that previously replaced sedimentary components.

It is well understood that grain size has a significant impact on a sedimentary rock's capacity to transport interstitial fluids. The impact is most noticeable in the traditional grain-size range for clays, i.e. < 3.9 m grain diameter. It's made worse by clay-sized particles' capillary retention, which reduces the cross-sectional area of pore accessible for free-fluid flow even more. This latter effect may be observed in water-wet rocks, as a difference in gas and brine permeability measured on the same core plug. This problem is exacerbated by the fact that fibrous, pore-bridging clay minerals like illite can reduce permeability by up to 30 times when compared to clean sand with otherwise comparable pore shape.

Permeability is a function of many parameters. The porosity of a rock, as well as the geometry of the pore network (tortuosity) and the grain shape, size, and composition, all affect the permeability of the rock. Although total porosity is a factor of permeability, the kind of porosity is also essential. Microporosity is usually ineffectual (Microporosity is considered as pore space that has a dimension approximately <1 micron). Different clay minerals have varying degrees of microporosity. Clay-rich matrix in sandstones, for example, includes significant void space, even if the pores are micrometer size or smaller and tend to be weakly linked, acting as a fluid flow baffle (Hurst & Nadeau, 1995). Clay minerals have a tendency to migrate and hence block interconnected pore throats, resulting in a severe permeability decrease. Also, an important factor is a mineralogical composition. For example, quartz and feldspar enhance permeability, while clay minerals and calcite tend to decrease it. Different clay-mineral cements differently affect permeability even because of their occupational positions within the pore space. Kantorowicz (1990) found that clay minerals placed tangentially to grain surfaces had a lower influence on permeability than perpendicular clay minerals or clay minerals that lie within pores and pore throats. Unless thin clay coatings on grain surfaces become interlaced at pore throats, thin clay coats on grain surfaces may have minimal influence on permeability. When thick coatings of illite or chlorite form, permeability can be severely reduced, especially in fine-grained sandstones, even if porosity is unaffected (Worden & Morad, 2003).

The type of clay mineral can have a variety of effects on permeability. Because clay rims are widespread surrounding detrital sand grains, grain–grain interfaces frequently consist of thin selvage of clay minerals (Worden & Morad, 2003). Mica-type minerals (e.g., illite) are believed to enhance pressure dissolution (chemical compaction) between quartz grains, while chlorite prevents it (Fisher et al., 2000). By assisting compaction and cementation, thin grain-coating illite may be able to actively induce quartz pressure dissolution and silica supply, reducing both sandstone porosity and permeability. Grain-rimming chlorite, on the other hand, can prevent quartz cementation and pressure dissolution (chemical compaction) in weakly compacted sandstones. Thus, even with a thin coating on quartz surfaces, chlorite can improve permeability by improving pressure solution and minimizing quartz overgrowth development.

Permeability reduction could be caused also by clay swelling (Worthington, 2009). This is a type of damage in which the permeability of the formation is lowered due to a change in clay equilibrium. When water-base filtrates from drilling, completion, workover, or stimulation fluids reach the formation, clay swelling occurs. Ion exchange or variations in salinity can induce clay swelling (Carcione et al., 2019). Only clays that come into close contact with the fluid flowing through the rock will react. Authigenic clays, certain detrital clays on pore boundaries, and unprotected clay cement are examples. Smectite and smectite-illite mixes are the most typical swelling clays, which form an almost impenetrable barrier to fluid movement when they are found in the reservoir rock's larger pores.

According to Gray & Rex (1966), clay minerals also can cause formation damage. Formation damage is a reduction in the initial permeability of the reservoir rock as a result of different wellbore activities, which can have a significant economic influence on the reservoir's production. The decrease of permeability in non-smectitic sandstones was linked to the migrating and pore-plugging properties of illite and kaolinite particles when the water moved through the formation. Similar results have been reported many times afterward in reservoir sandstones, although at the time, the major cause for formation damage was thought to be the swelling of smectitic clays (Wilson et al., 2014). Formation damage in sandstones is considered to be caused by a variety of mechanisms involving clay minerals. Swelling of smectitic clays, dispersion, and migration of a range of clay minerals, including smectites but mostly involving kaolinite and illite, and transition of clay minerals to other mineral phases are all examples of possible reasons of formation damage in sandstones (Wilson et al., 2014).

Clay minerals do not always represent poor reservoir quality; in fact, they can be a positive indicator of high reservoir quality. For example, chlorite coatings on sand grains can help to retain reservoir quality by preventing quartz cementation

(Worthington, 2009). The greater content of kaolinite might sometimes indicate increased porosity. The reason for this is that when acid dissolves feldspar to form kaolinite, porosity is produced. For example, a case study from Huagang Formation in the Xihu Sag, East China Sea Basin resulted that higher porosity exists in good-quality reservoirs with greater chlorite coating coverage ratios. Kaolinite tends to change into different clays in subsequent diagenesis, therefore the connection between kaolinite and reservoir characteristics does not show the true influence of kaolinite on reservoirs (Sun et al., 2019).

8. Methodology

For our study, we took data of mineralogical analysis of South Caspian Basin from the research of Abdullayev and Leroy (2016). In the research of Abdullayev and Leroy (2016) 322 samples were collected from all suites of the Productive Series and analyzed in the Institute for Geophysics and Geology at the University of Leipzig for two different analyses, X-ray analysis of clay minerals and X-ray analysis of bulk sediments. They concentrated on the occurrence and provenance of the main clay mineral groups illite, chlorite, kaolinite, and smectite. Clay minerals were identified by their basal reflections and their relative percentages were determined using empirically estimated weighting factors.

In our research sediments of the South Absheron Offshore Zone (Shah Deniz field) is the subject of our investigation. So we took the data of X-ray diffraction of clay fraction from 44 samples of Fasila zone and 63 samples of Balakhany VII sub-suite and build a diagram to see the distribution of each clay mineral through the depth.

Then we investigated the distribution of the main detrital clay minerals by using the available data from Abdullayev and Leroy researches and correlate them with petrophysical data from SDX-5Y well. This can help identify the impact of clay minerals on reservoir quality in the Fasila suite and Balakhany VIII sub-suite sandstones of South Absheron Offshore Zone (Shah Deniz field).

Well log data is analyzed to evaluate rock characteristics including mineralogical composition, sedimentary structure, and petrophysical properties, such as porosity and permeability (Jafarzadeh et al., 2019). The classification of facies based on petrophysical characteristics and their investigations in the context of petrofacies can be a useful tool for classifying reservoir zones and identifying high-quality reservoir regions.

The porosity and permeability were extracted from the SDX-5Y well composite log with the help of NeuraLog software. Obtained porosity and permeability values from Balakhany_VIIIC, Fasila_A, and Fasila_B_SP3 zones were composed with the X-ray diffraction of clay fractions from Fasila and Balakhany VIII zones (Abdullayev and Leroy, 2016).

We analyzed Porosity and Permeability distribution in these intervals. Through this part of research 128 porosity, and 571 permeability dots for Fasila and 555 porosity and 571 permeability dots for Balakhany VIII, were extracted with the help of NeuraLog and plotted in the diagram.

Further, gained values of porosity and permeability from the well were correlated with the data of the percentage of smectite, chlorite, illite, and kaolinite in each region. R^2 was used to show each mineral's impact on porosity and permeability on the diagram. R^2 or the coefficient of determination is a measure of the relationship between two data sets used in a mathematical model.

9. Results:

9.1 Characterization of clay minerals in the Pliocene Productive Series

In the first part of our study, we are using data from X-ray diffraction of clay fraction in Fasila zone (44 samples) and in Balakhany VII sub-suite (63 samples) to create a diagram to show the distribution of each clay mineral through depth.

The thickness of the Fasila zone is 25.33 mbsf and Balakhany VIII sub-suite is 84.34 mbsf. The results are shown separately for each region to make it simpler to visualize. The minimum, mean, and maximum values for each interval are presented. All detailed data are listed in the appendix.

Fasila

Fasila suit start at 6382.31 mbsf and ends at 6401.64 mbsf. (Fig. 7)

Smectite concentrations in the Fasila Suite range from 15% to 45 %, with an average value of around 29%. From 6401.50 mbsf to 6395.19 mbsf, the most smectite is observed. The quantity of smectite decreases between 6390.50 mbsf and 6382.50 mbsf.

Illite is the most common clay mineral in Fasila Suite, as far as in Balakhany VIII with a concentration of about 48 %, ranging from 38 to 65 %. From 6390.50 m to 6382.50 m, the data indicate an upward trend. The minimum value of 38% is obtained at 6398,35 mbsf.

The chlorite content ranges from 7% to 34%, with an average value of 13%. The minimum value of 7% corresponds to 6398.35 mbsf. The highest amount of chlorite (34%) is observed at 6391.18 mbsf.

The content of kaolinite is lowest again, ranging from 2% to 17%, with an average concentration of 10%.

Balakhany VIII

Balakhany VIII suit starts at 5913.08 mbsf and ends at 5997.42 mbsf. (Fig. 8)

The average quantity of smectites in the Balakhany VIII sub-suite is 31 %, with a range of 4 %to 46 %. The maximum value of 46 % corresponds to 5927 mbsf. A minimum amount of smectite (3.6 %) we observe at 5923.5 mbsf.

The average illite concentration is 44 %, although it varies between 31 and 62 %. A maximum amount of 61,7% has been obtained at 5923.5 mbsf. Minimum is 31% of illite at 5973.3 mbsf. As we observe, Illite has the highest concentration through the sub-suite.

The chlorite content ranges from 7% to 26%, with the average being 14 %. The minimum value of 7% corresponds to 5996.5 mbsf. The highest amount of chlorite (7%) is observed at 5923.5 mbsf

The quantity of kaolinite varies from 0.2 % to 19 %, with a kaolinite content of 10% on average. The lowest clay mineral content through the sub-suite. The minimum value of 0.2 % has been obtained at 5930.39 mbsf. The highest (19.2%) at 5922.25 mbsf

Fig. 8. X-ray diffraction of clay fraction; South Absheron Offshore Zone (Shah Deniz) versus depth. Balakhany VIII zone

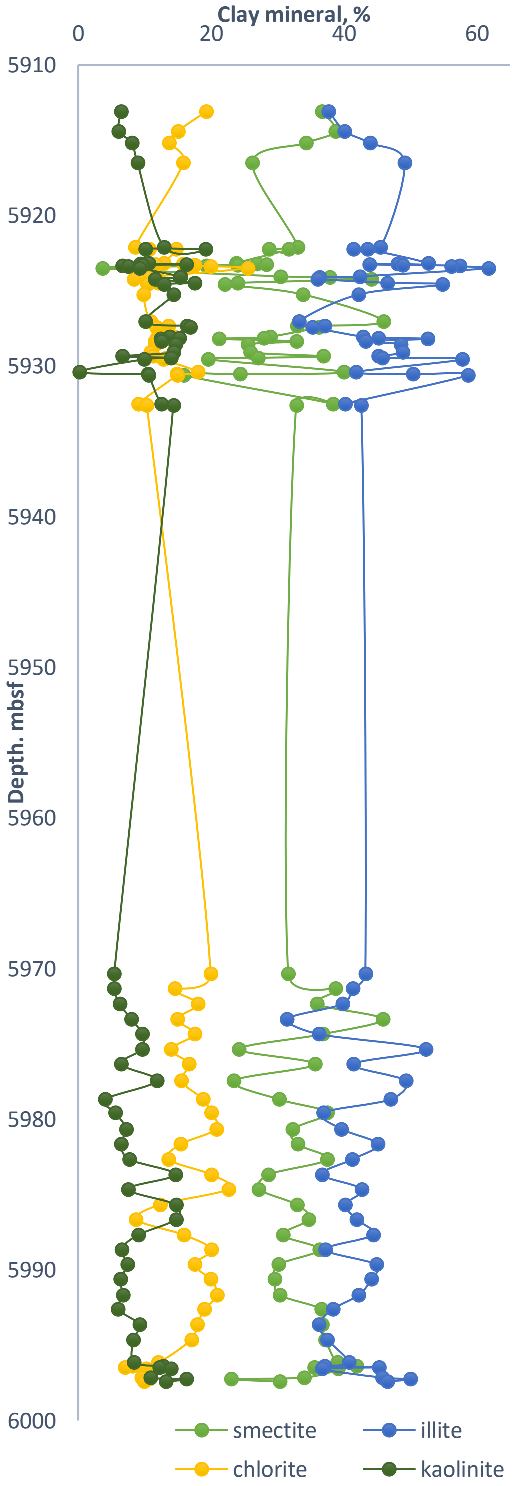
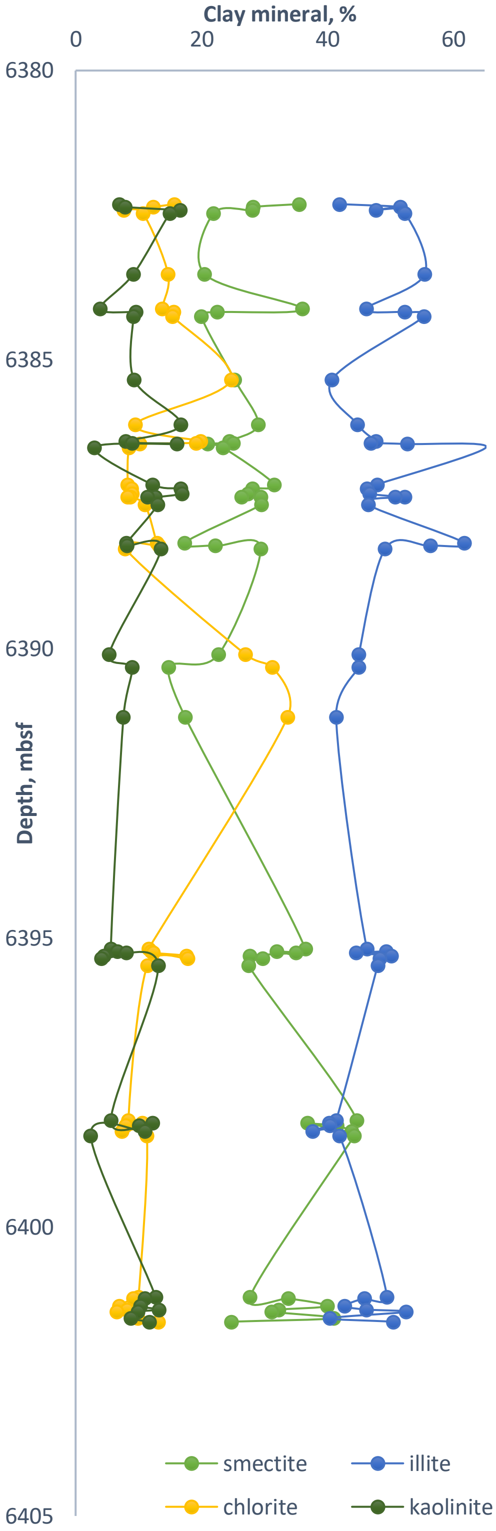


Fig. 7 X-ray diffraction of clay fraction; South Absheron Offshore Zone (Shah Deniz) versus depth. Fasila zone



9.2 Characterization of reservoir quality in the Pliocene Productive Series

The next step is to use NeuraLog software to extract the porosity and permeability data from the SDX-5Y well composite log. In these intervals, we investigated the distribution of porosity and permeability. 128 porosity and 571 permeability dots for Fasila and 555 porosity and 571 permeability dots for Balakhany VIII were obtained and presented in this diagram.

Fasila

The green trend line (Fig. 11) shows the distribution of porosity through the depth in the Fasila suite. Overall, porosity in this region is less than in the previous unit. The porosity is changing from 0.01 to 0.16, the average is about 0.1. Starting from the 6382 mbsf and 0.03% of the porosity trend line tends to increase till the 0.16% and then fluctuate with the average values of 0.08 % till the end. Minimum porosity is in the depth of 6384 mbsf, the maximum value is in the depth of 6391 mbsf.

The yellow trend line (Fig. 12) shows the distribution of permeability through the depth in the Fasila suite. Permeability values are also lower than in the Balakhany VIII unit. Values change from 6322 mD to 12333 mD, average is about 9920 mD. Starting with the approximate value of 7800 mD trend line is fluctuating and then from the 6385 m sharply increase up to almost 12000 mD. Then we see a smooth increase till 7600 mD at depth of 6400 mbsf. Then, again increasing trend till 11700 mD. Till the end, we see unstable fluctuations with approximate values of 10000 mD.

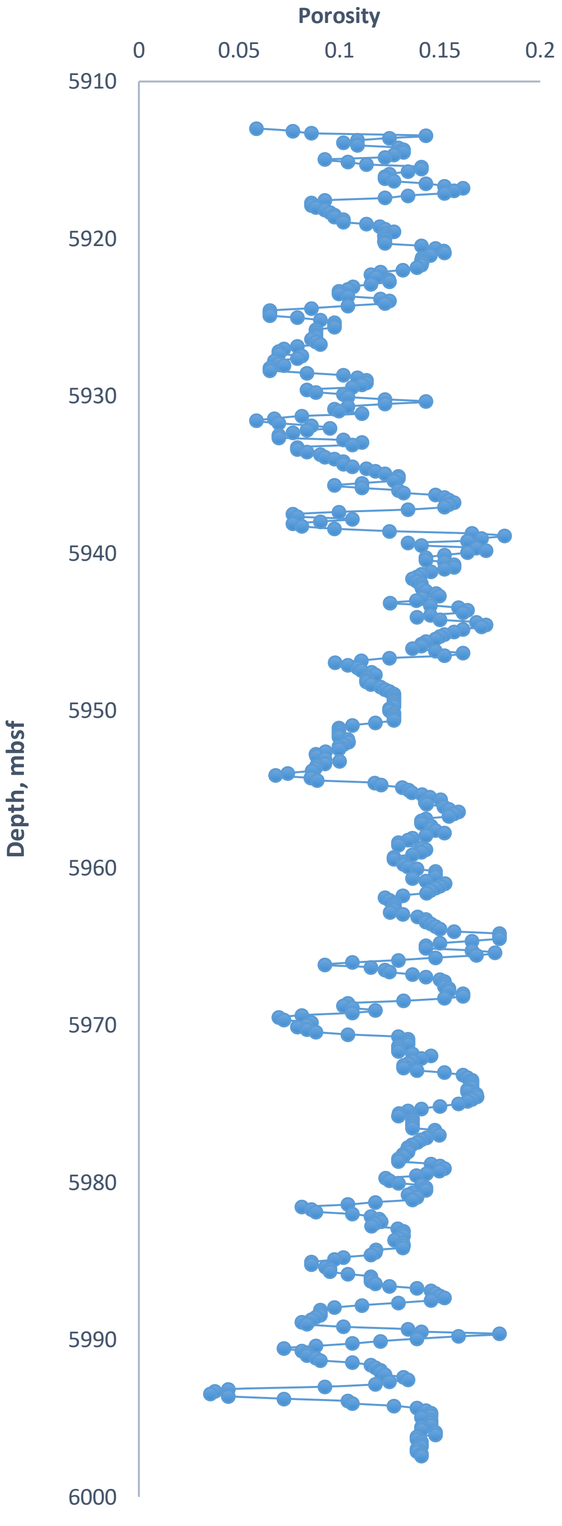
Balakhany VIII

The blue trend line (Fig. 9) shows the distribution of porosity through the depth in the Balakhany VIII sub-suite. Starting from the 5913.08 mbsf we see the increasing trend up to 0.16% of porosity. Then, from 5917 mbsf trend is tend to decrease to 0.06% of porosity in 5928 mbsf. Slight increase of up to 0.16% of porosity at 5939 mbsf. Then again decrease to 0.09% at approximately 5954 mbsf. And till the end, we observe fluctuating line with the average porosity between 0.12-0.15 %.

The Average porosity value through the Balakhany VIII is about 0.12 but fluctuates between 0.035 and 0.18. The maximum porosity value is at 5938.89 mbsf, minimum at 5993.45 mbsf.

The orange trend line (Fig. 10) shows the distribution of permeability through the depth in the Balakhany VIII sub-suite. Starting with the approximate values of 12300 mD trend line is slightly increasing up to 16000 mD at depth of 5938 mbsf. Then, we see a decreasing trend till 11000 mD at 5954 mbsf. Then, the trend line is increasing and fluctuates with approximate values of permeability between 13000-17000 mD until the end.

Permeability values range between 10379 mD and 18182 mD. The average permeability of the Balakhany VIII is about 14384.5 mD.



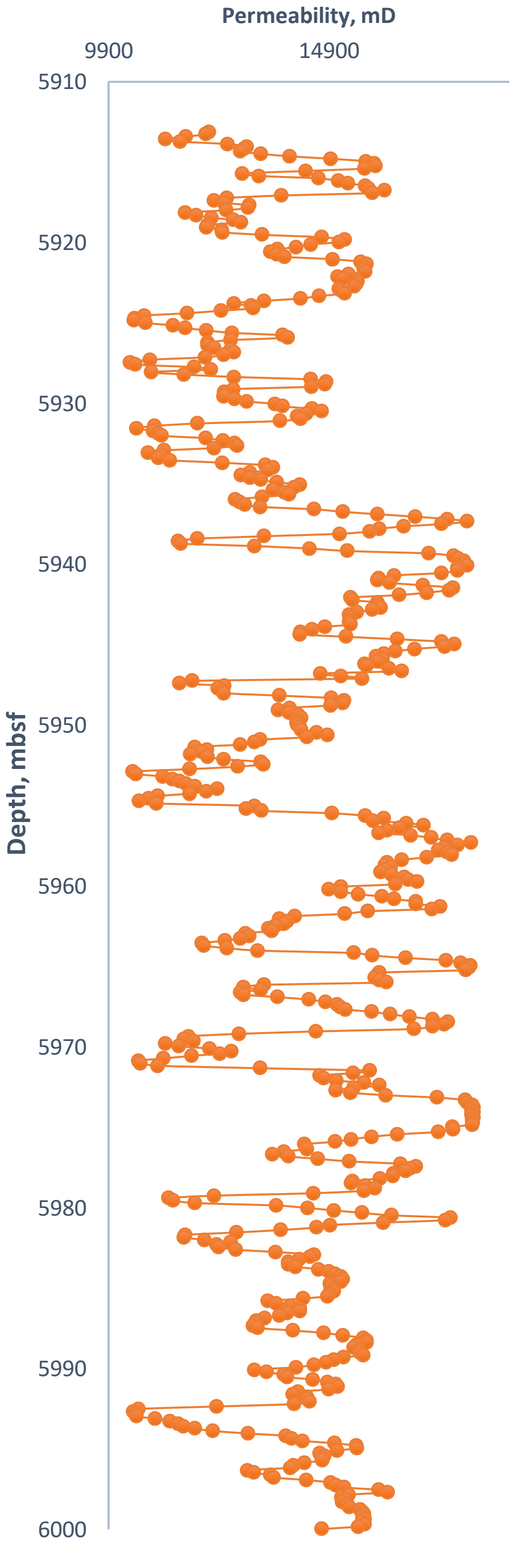
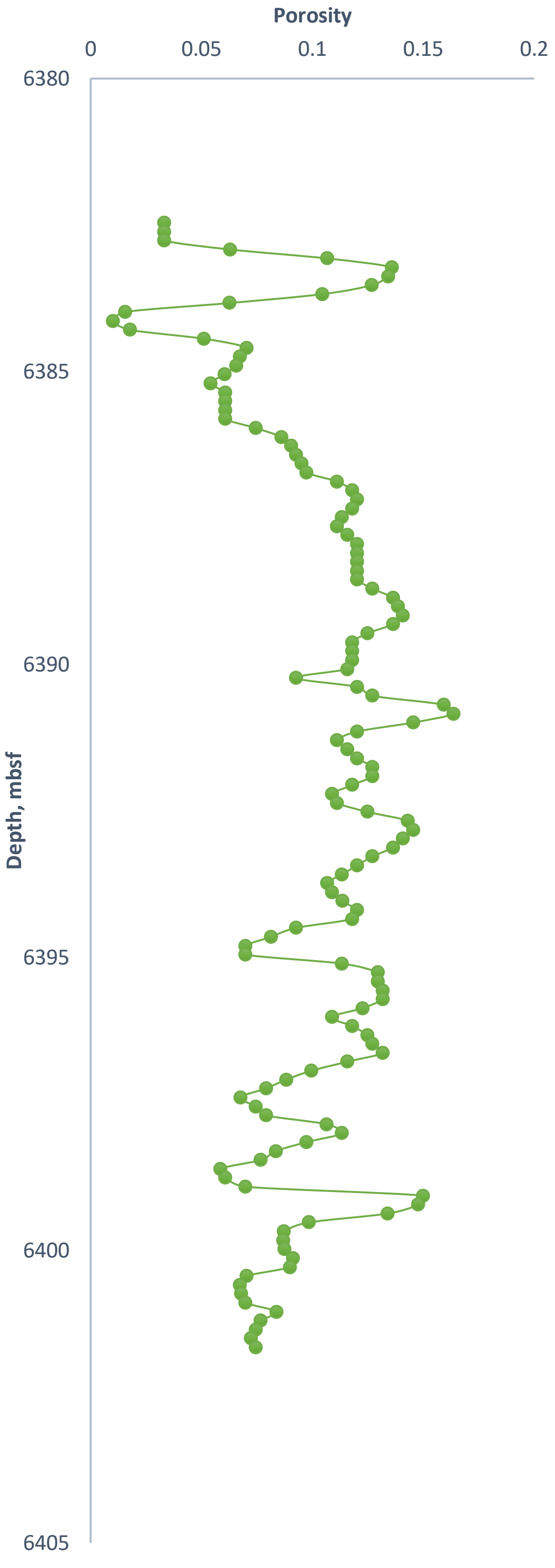


Fig.9 Porosity versus depth of the Balakhany VIII sub-suite

Fig. 10 Permeability versus depth of the Balakhany VIII sub-suite



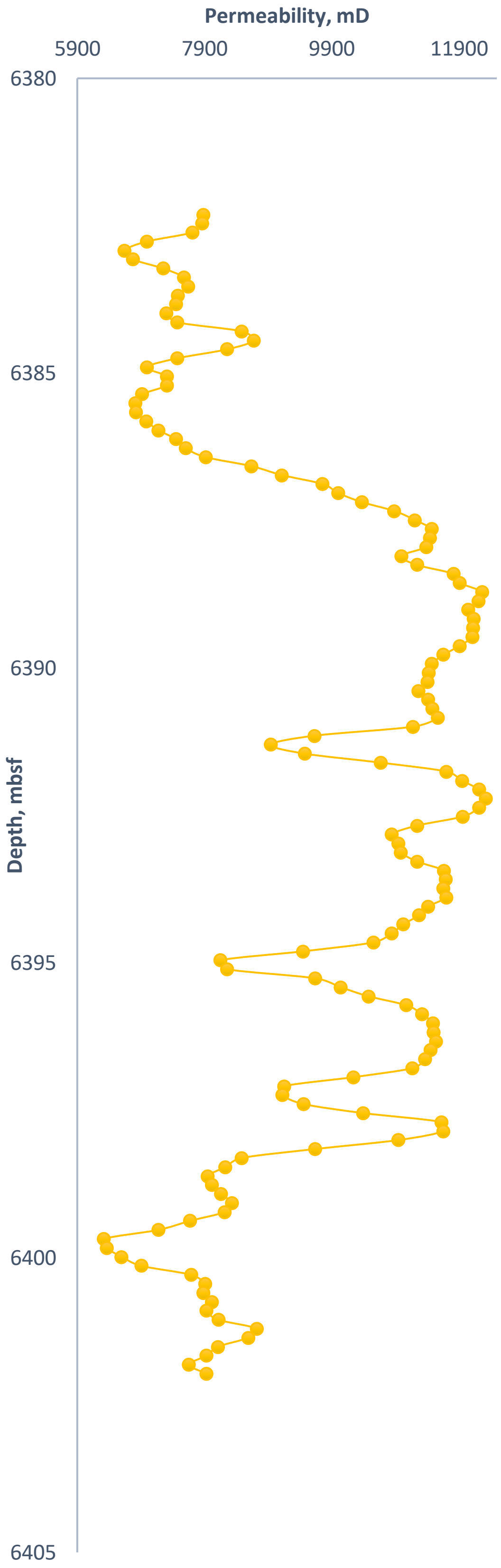


Fig.11 Porosity versus depth the Fasila suit

Fig. 12 Permeability versus depth the Fasila suit

In Balkhany VIII smectite correlation with porosity gave a result of $R^2 = 0,0016$; it means that there is no dependence between smectite and porosity. Illite versus porosity diagram show correlation $R^2 = 0,0041$. Chlorite $R^2 = 0,0012$, Kaolinite $R^2 = 0,0478$. All parameters of R^2 are close to zero which means that between these two variables there is no interconnection.

Permeability correlation with clay mineral content also did not show any dependence. Smectite $R^2 = 0,0001$; Illite $R^2 = 0,0119$; Chlorite $R^2 = 0,0066$; Kaolinite $R^2 = 0,014$

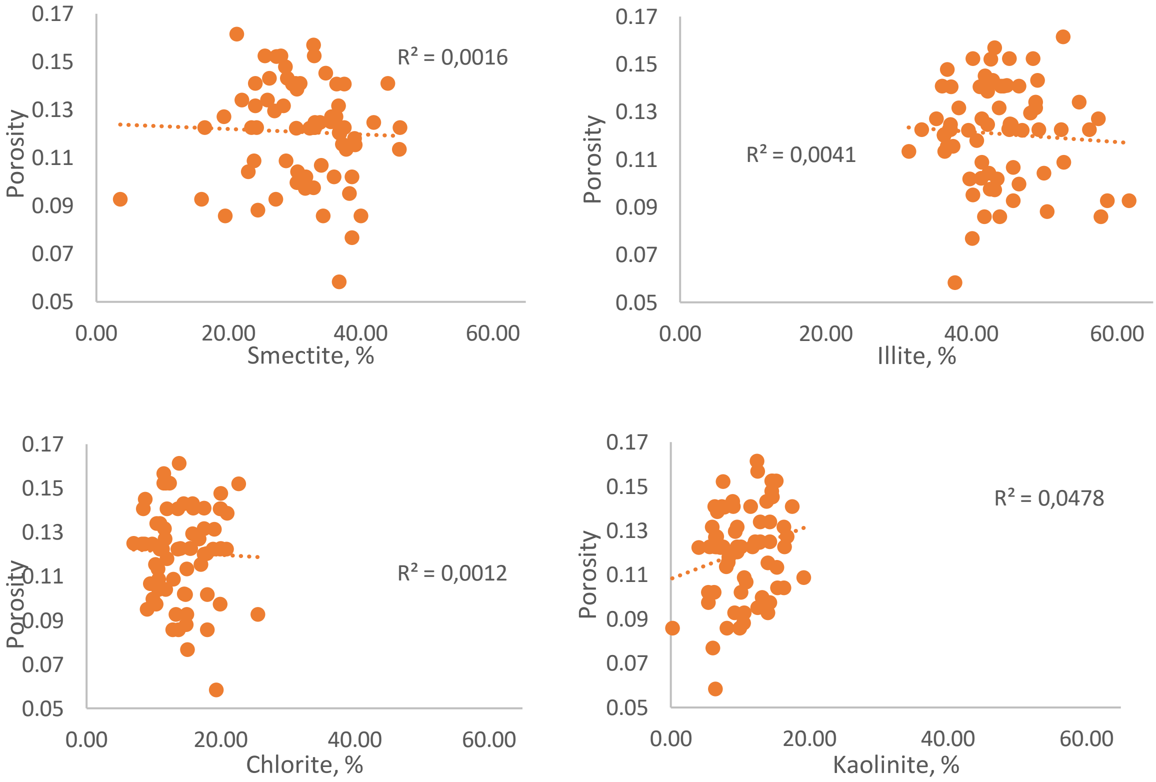


Fig. 13 Influence of detrital clay mineral content (%) on porosity in Balakhany VII sub-suite

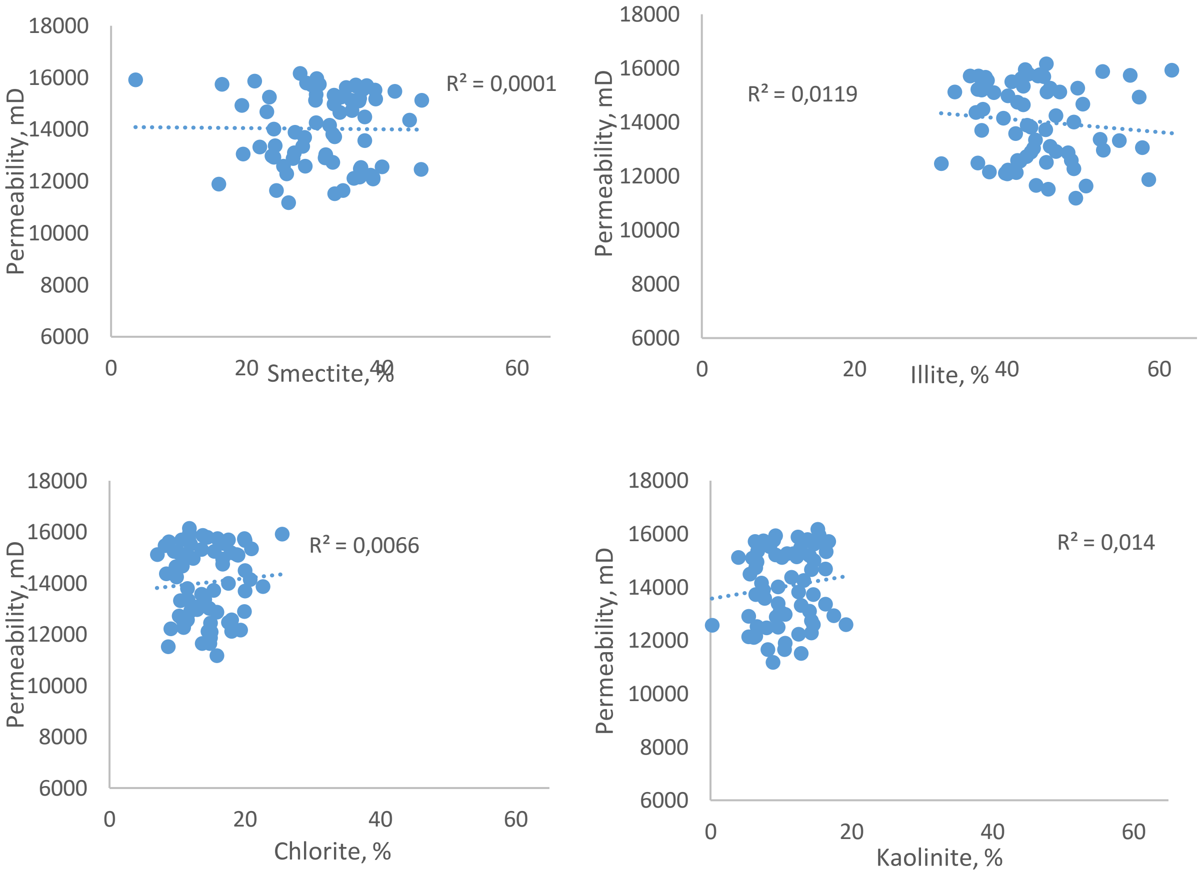


Fig. 14 Influence of detrital clay mineral content (%) on permeability in Balakhany VII sub-suite

In Fasila suit Porosity versus Clay content diagrams slightly differ for Smectite and Illite: Smectite $R^2 = 0,1705$; Illite $R^2 = 0,1644$; These values show a few possible correlation points between clay mineral content and porosity in this region. Chlorite $R^2 = 0,0015$; Kaolinite $R^2 = 0,021$. Chlorite and Kaolinite again gave absolutely no dependence.

Permeability correlation with clay mineral content in Fasila suit also did not show any dependence. Smectite $R^2 = 0,0001$; Illite $R^2 = 0,0119$; Chlorite $R^2 = 0,0066$; Kaolinite $R^2 = 0,014$

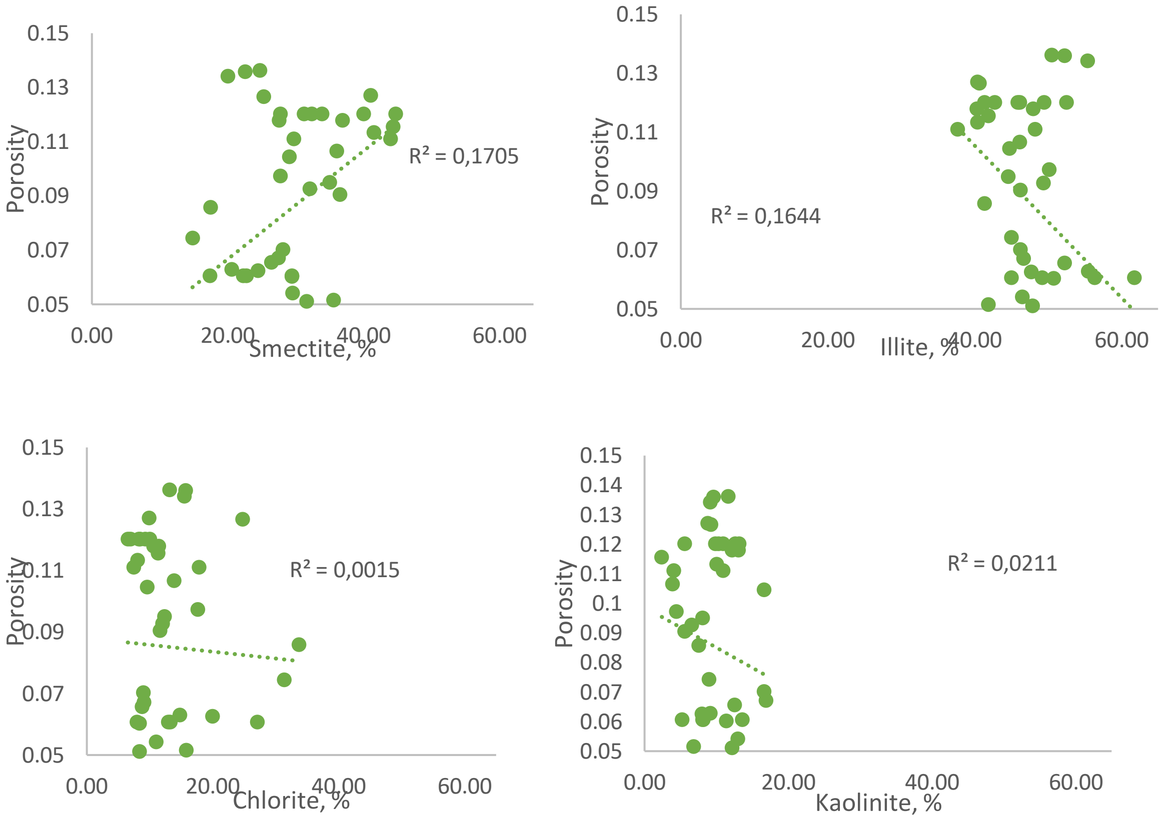


Fig. 15 Influence of detrital clay mineral content (%) on porosity in Fasila suit

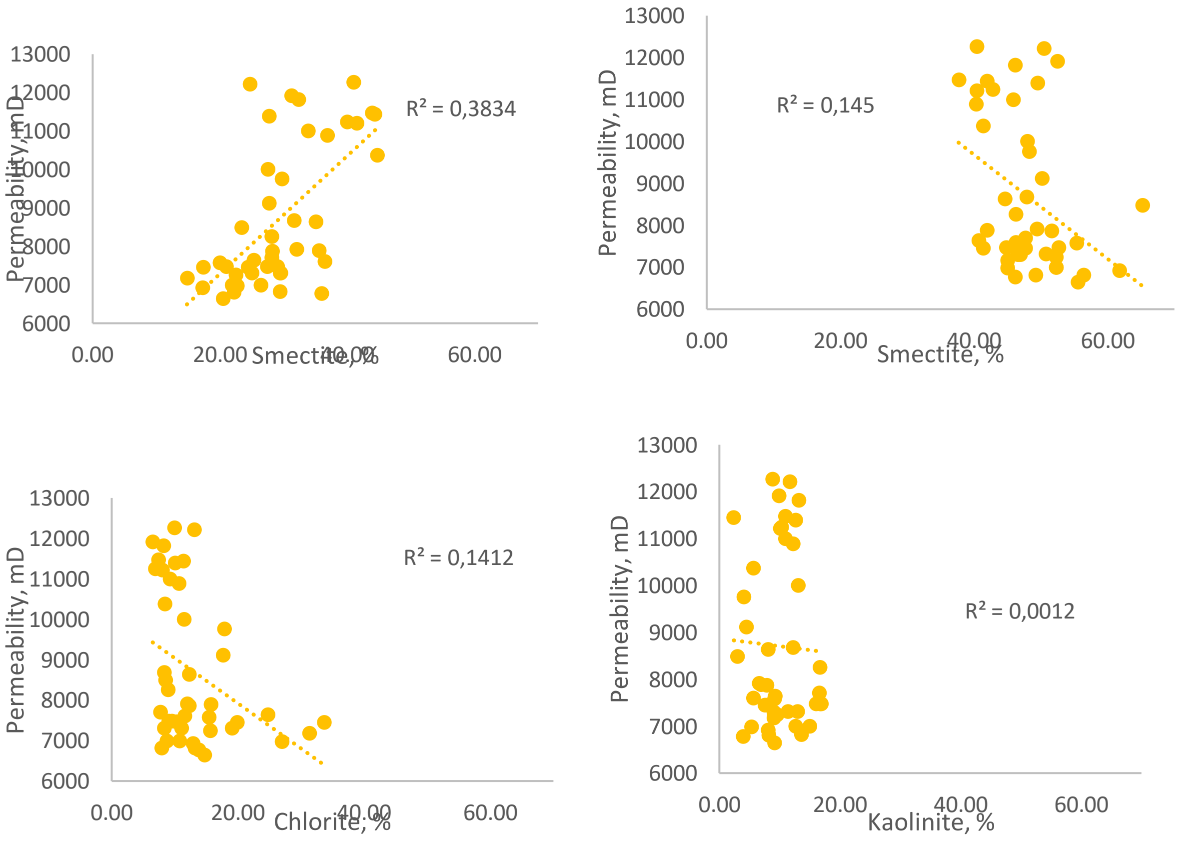


Fig. 15 Influence of detrital clay mineral content (%) on permeability in Fasila suit

10. Discussion

Since clay minerals have an impact on rocks' properties, it's essential to investigate the role of smectite, illite, chlorite, and kaolinite in the reservoir quality of the PS in the Shah Deniz field.

In spite of that, our data showed a nearly negative correlation with porosity and permeability in the cross plot, we can see some relation between clay mineral assembalges and porosity and permeability. Porosity and permeability parameters in these layers suggest good reservoir quality. It indicates that these clay minerals have no negative impact on reservoir quality. Let's compare both porosity and permeability distributions with clay mineral fractions in the same zones.

Fasila zone

The start of the Fasila zone is described with fluctuating points of porosity and permeability with average values of 0.06 and 6385 mD, respectively. (Fig. 18) Clay minerals fractions are also fluctuating and there is no exact trend of increase or decrease. (Fig. 19)

From 6386 mbsf till 6388 we see a sharp increase in porosity and permeability values. As goes to clay minerals distribution, we could observe a slight decrease of smectite, chlorite, and kaolinite trend lines. Illite %age is slightly increasing.

Trend lines between 6388 mbsf and 6394 mbsf are fluctuating with the average values of porosity 0.12 and for permeability 11500 mD. There are not many points of clay minerals distribution in that interval, so we could not predict any correlation. From 6396 we observe a slight reduction of porosity and a sharper reduction of permeability. Kaolinite and chlorite are almost not changing in that interval. The first part of that interval chlorite is seemed to increase, but then it is decreasing a little bit. The illite trend line is decreasing and staying almost stable.

Balakhany VII sub-suite

Starting from the beginning till ~ 5917 mbsf we see an increasing trend both for porosity and permeability values (Fig. 16). As goes to clay minerals distribution (Fig. 17), we observe a sharp increase of illite; smectite, and chlorite slightly decreasing and kaolinite has a very fluctuating but increasing trend till ~ 5933 mbsf.

The impact of illite on reservoir quality was described in previous studies from both positive and negative sides. Illite is made up of fragmented, flaky, or fibrous particles that decrease the size and interconnectivity of pores and throats (Meng, et al., 2011). The positive effect was investigated according to that illite coatings can potentially improve reservoir quality by limiting the development of quartz cement and also because illite is not so much expandable clay as other ones. (Worden, Griffiths, & Utley, 2017).

From ~ 5917 till ~ 5933 both porosity and permeability are decreasing, with sharp fluctuations. Clay minerals are distributed differently: kaolinite and smectite have a slightly increasing trend line, but illite and chlorite are decreasing. So, again, we see some connection between changing of illite percentage and reservoir quality parameters.

Chlorite coatings are commonly recognized as a key element in ensuring better reservoirs characteristics by preventing quartz cement formation by separating quartz grains and pore fluids and improving silica solubility by controlling pore fluid pH. (Berger, Gier, & Krois, 2009; Billault, Beaufort, Baronnet, & Lacharpagne, 2003; Gould et al., 2010;). Others assume that lithology, rather than chlorite coatings, is more important in producing high-quality reservoirs (Yang et al., 2013; Yao, Wang, Zhang, & Li, 2011) because chlorite's plentiful intercrystalline pores provide pathways for pore fluids to cement on quartz surfaces and might damage reservoirs by trying to block pores. (Yang et al., 2013; Yao, Wang, Zhang, & Li, 2011). It remains unclear which component creates high-quality reservoirs when there are both positive correlations between chlorite and lithologies and reservoir quality. In this part of Balakhany VII, we do not see the impact of chlorite on reservoir characteristics.

From ~ 5933 mbsf till 5970 mbsf there are no samples of clay mineral fraction. Starting from 5970 mbsf we see an increase of porosity from approximately 0.072 till 0.168, and permeability also positively changes from approximately 11600 mD to 18100 mD. Smectite and Illite at the same depths are fluctuating, but we could observe a slightly increasing trend of kaolinite percentage. Chlorite is decreasing. So, we could again assume that chlorite does not give a negative impact on reservoir quality in that interval. As goes to kaolinite, there are different opinions on its influence on reservoir parameters, but higher kaolinite concentration might sometimes imply increased porosity. The reason for this is that porosity is generated when acid dissolves feldspar to make kaolinite.

Next interval from 5975 mbsf till 5993 mbsf, we see a reduction of both reservoir parameters. The slight reduction we could observe in Illite distribution, which again proves a correlation between Illite fraction and porosity/permeability distribution. Kaolinite and chlorite are almost stable in this interval, but smectite values are increasing.

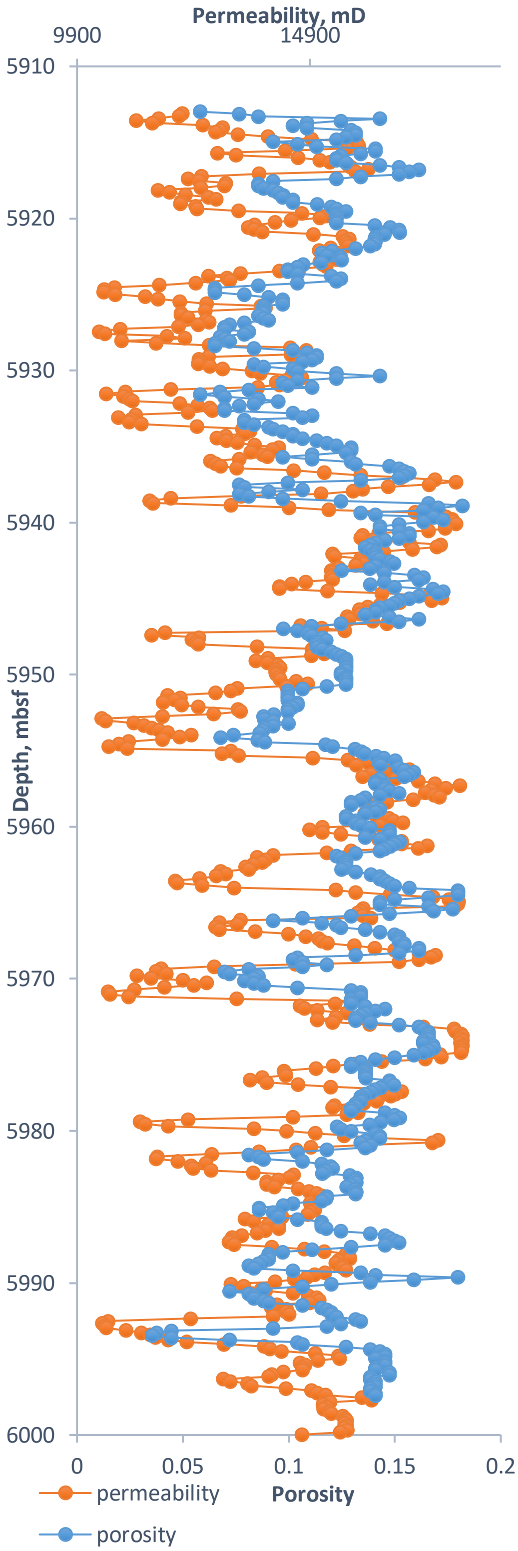


Fig. 16 Porosity and permeability distribution in Balakhany VII sub-suite

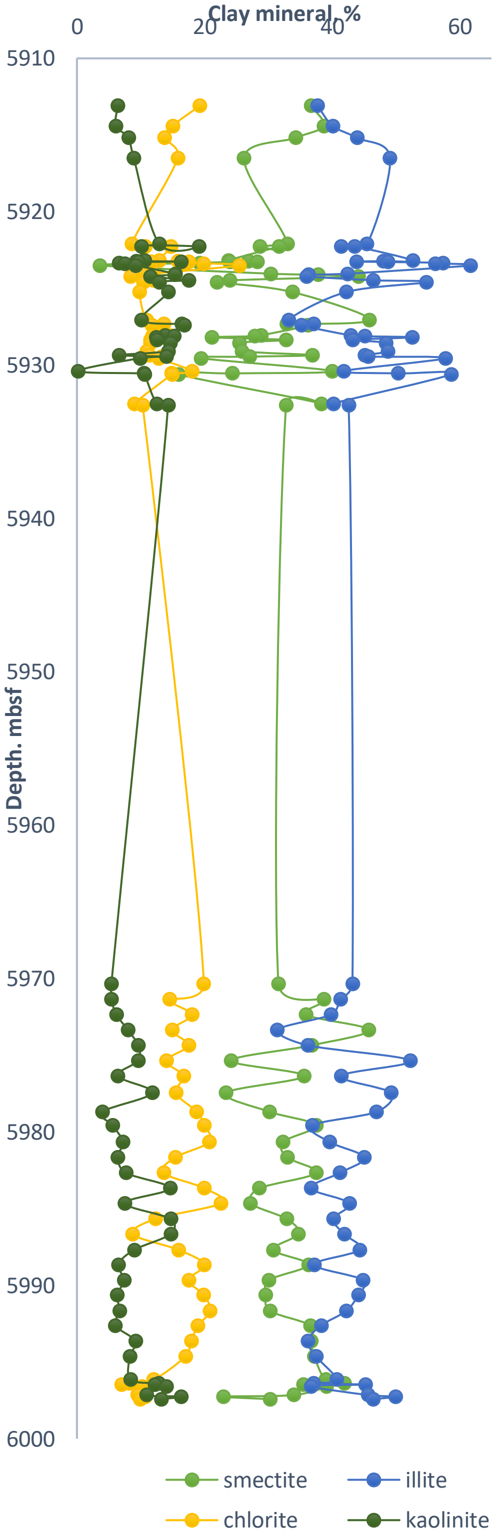


Fig. 17 Clay mineral (%) distribution in Balakhany VII sub-suite

It’s believed that smectite and smectite-illite mixes are the most typical swelling clays, which could form an almost impenetrable barrier to fluid movement when they are found in the reservoir rock's larger pores. As we see in this interval porosity and permeability reduction may be caused by the increase of smectite.

We could make an assumption that clay minerals distribution does not have a great influence on reservoir quality. Only for Illite, we could see some positive responses of porosity and permeability, especially its better seen in the Balakhany VII sub-suite.

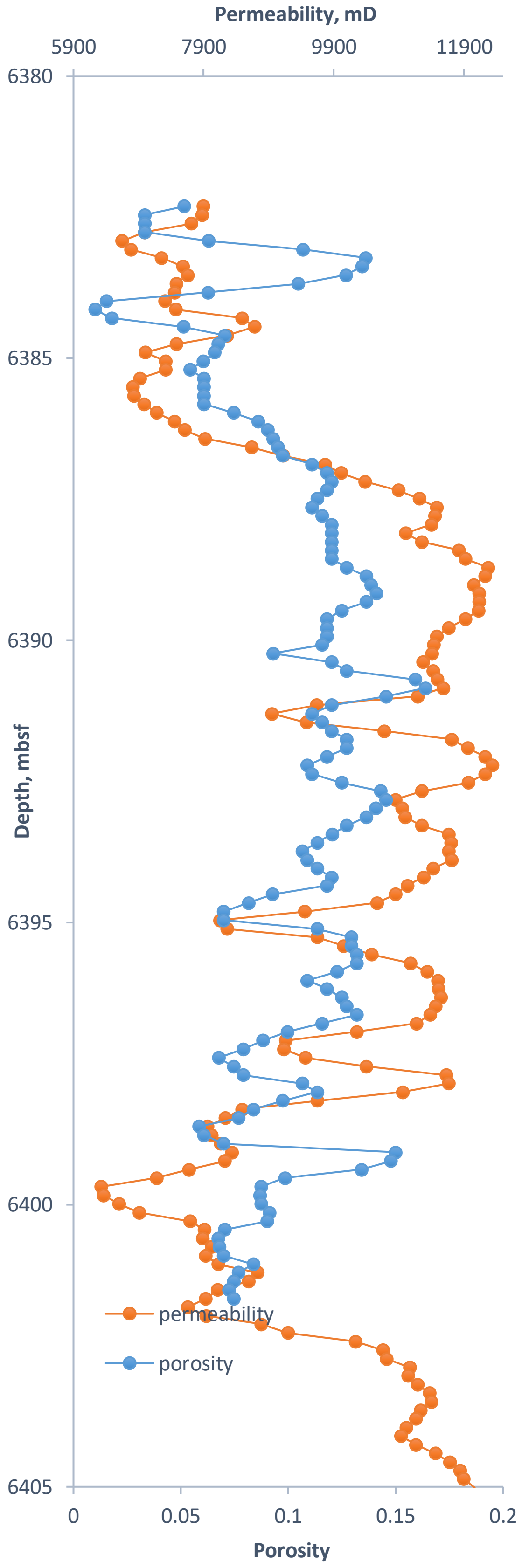


Fig. 18 Porosity and permeability distribution in Fasila suite

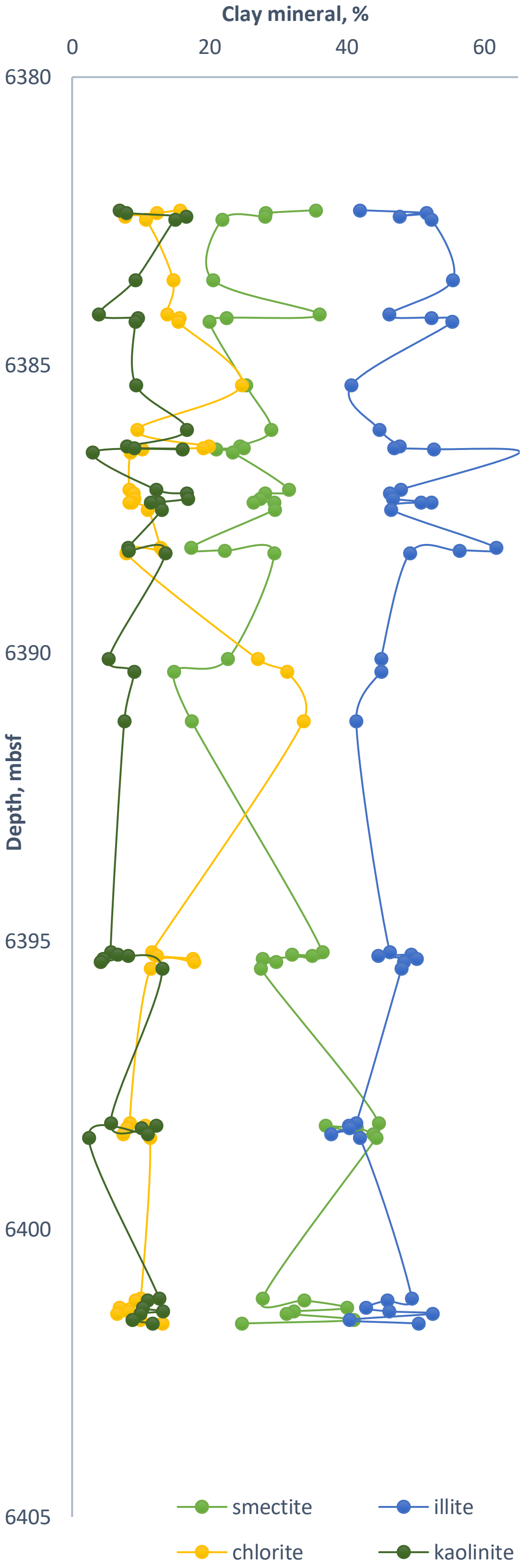


Fig. 19 Clay minerals distribution in Fasila suite

11. Conclusion

Clay minerals are the essential composition of reservoir rocks that can help in generating and storing hydrocarbons. The presence of clays strongly impacts the physical and chemical characteristics of sandstones. Regionally, clay minerals may be studied to interpret and analyze sedimentation, burial, and temperature history as well as predict the sedimentary environment and correlate layers, etc. The presence of clay minerals in reservoir rocks has a significant influence on reservoir parameters like porosity and permeability, as well as the measured physical data required to assess reservoir quality.

Clay minerals information is also used by geologists to understand the burial diagenetic process and identify pore type and evolution. Even though they are usually considered to be detrimental to reservoir quality because they can plug pore throats and are easily compacted, other diagenetic processes may enhance porosity and permeability by providing clay dissolution, creating micropores in clays, and coating chlorite on grains to prevent quartz cementation.

Based on the clay mineral distribution of both the Fasila and Balakhany VIII sub suits of the Productive Series and logging data of the porosity and permeability of the same zones, the effect of clay minerals on reservoir quality has been shown.

The clay minerals (smectite, illite, chlorite, kaolinite) derived from Balakhany VIII sub-suite did not show great impact on the change of porosity and permeability values. Chlorite and kaolinite do not seem to have an impact on reservoir quality, but in some observed interval, porosity and permeability decrease may be caused by the increase of smectite. Illite in some regions had a positive effect on both porosity and permeability parameters.

Almost the same trend of clay minerals effect on reservoir quality is observed in Fasila suit. Kaolinite and chlorite are almost not changing porosity and permeability values in the interval. Smectite is reducing the reservoir parameters, but illite has a positive effect on both porosity and permeability distribution.

These results indicate that clay minerals could not be the primary factors that control and affect porosity and permeability. We couldn't find any evidence of negative influence of all clay minerals on porosity or permeability, it is strongly dependent on the type of clay mineral. Moreover, in spite the fact that clay minerals are assumed to be a damaging component of reservoir, there was even detected some positive influence of illite distribution on reservoir characteristic.

These findings point to the need for additional research into the influence of clay minerals on reservoir quality. It may be accomplished by experimenting with various mathematical models and expressions and comparing them to one another. A deeper investigation of fluid densities, tortuosity, grain size, and other important variables influencing reservoir performance could result in a better understanding of subsurface fluid flow processes. Furthermore, having more data (wells) to work with might yield more valuable outcomes.

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Appendix

Depth (mbsf)	Smectite %	Illite %	Chlorite %	Kaolinite %
Balakhany VIII sub-suite				
5913,08	36,7	37,7	19,3	6,4
5914,4	38,7	40,1	15	6,1
5915,18	34,3	43,9	13,7	8,1
5916,5	26,2	49,1	15,8	8,9
5922,09	33	45,5	8,6	12,9
5922,25	28,7	41,4	10,7	19,2
5922,25	31,7	43,5	14,7	10,1
5923,18	23,8	52,7	12,9	10,6
5923,22	26,9	48,1	15,8	9,3
5923,25	28,3	43,8	11,6	16,3
5923,28	24	48,8	17,5	9,6
5923,33	19,3	57,4	16,7	6,6
5923,37	16,4	56,2	19,9	7,5
5923,5	3,6	61,7	25,5	9,2
5924,04	30,4	42,4	11,8	15,4
5924,11	37,8	36,3	10,6	15,3
5924,22	44,1	36	8,4	11,5
5924,47	24	46,5	12	17,5
5924,59	22	54,8	10,4	12,9
5925,24	33,8	42,2	9,8	14,3
5927,05	45,9	33,2	10,9	10,1

5927,33	32,9	37,1	13,6	16,4
5927,41	36,2	35,2	11,7	16,8
5928,06	28,9	42,9	14,4	13,8
5928,12	27,9	45,2	11,8	15,2
5928,19	21,2	52,6	13,8	12,4
5928,36	32,8	43,2	11,5	12,5
5928,55	25,5	48,5	11,5	14,6
5929,09	25,9	48,8	10,9	14,3
5929,35	36,9	45,2	11,3	6,6
5929,45	27,1	45,7	13,3	14
5929,55	19,5	57,8	12,8	9,9
5930,39	40	41,8	18	0,2
5930,54	24,4	50,4	14,8	10,5
5930,59	15,9	58,7	14,9	10,6
5932,51	38,3	40,2	9	12,5
5932,6	32,8	42,6	10,3	14,3
5970,32	31,6	43,2	19,9	5,4
5971,33	38,7	41,3	14,5	5,4
5972,35	35,9	39,8	18	6,2
5973,35	45,8	31,4	14,9	8
5974,35	36,8	36,2	17,5	9,6
5975,35	24,2	52,3	14	9,6
5976,35	35,6	41,4	16,7	6,4
5977,45	23,4	49,3	15,5	11,8
5978,68	30,2	47	18,8	4
5979,57	37,5	36,9	20	5,6
5980,65	32,3	39,6	20,8	7,2
5981,66	33	45,1	15,4	6,4
5982,67	37,5	41,2	13,6	7,7
5983,67	28,6	36,7	20	14,6
5984,64	27,2	42,7	22,6	7,5
5985,67	32,9	40,2	12,3	14,7
5986,65	34,7	41,9	8,7	14,7
5987,68	30,8	44,4	15,9	9
5988,65	36,3	37,2	20	6,5
5989,65	30,1	44,9	17,5	7,4
5990,63	29,6	44,1	19,9	6,3
5991,67	30,3	42,2	20,9	6,7
5992,61	36,6	38,3	19	6
5993,64	36,7	36,2	17,9	9,2
5994,63	37,2	37,5	17	8,3
5996,15	39	40,7	12	8,4
5996,38	41,9	37,1	8,2	12,8
5996,47	35,5	45,3	7	12,2
5996,57	39,1	36,7	10,2	14

5997,15	34	45,7	9,5	10,9
5997,25	23	50	10,7	16,3
5997,42	30,3	46,5	9,9	13,2
Fasila Suite				
6382,31	35,5	41,9	15,7	6,9
6382,36	28,2	51,6	12,3	7,9
6382,42	28,1	47,7	7,7	16,6
6382,47	21,9	52,3	10,7	15
6383,52	20,5	55,5	14,7	9,2
6384,12	36	46,2	13,8	3,9
6384,18	22,5	52,3	15,6	9,6
6384,25	20	55,4	15,4	9,2
6385,35	25,3	40,7	24,7	9,3
6386,12	29	44,8	9,5	16,7
6386,41	24,4	47,7	19,9	8
6386,44	25	46,9	19,1	9
6386,46	21	52,7	10,2	16,1
6386,52	23,4	65,2	8,5	3
6387,16	31,6	47,9	8,3	12,2
6387,23	28,1	46,3	8,9	16,7
6387,32	27,4	46,7	9	16,9
6387,38	26,4	52,3	8,7	12,6
6387,38	29,4	50,8	8,3	11,4
6387,51	29,5	46,5	11	13
6388,17	17,3	61,8	12,9	8,1
6388,22	22,2	56,4	13,2	8,2
6388,27	29,4	49,2	7,9	13,6
6390,1	22,7	45	27	5,3
6390,32	14,8	45	31,3	9
6391,18	17,4	41,4	33,7	7,6
6395,19	36,5	46,3	11,6	5,6
6395,23	32	49,4	12	6,6
6395,26	35	44,6	12,3	8,1
6395,31	27,7	50,2	17,6	4,5
6395,36	29,7	48,3	17,8	4,1
6395,48	27,5	48	11,4	13,1
6398,16	44,7	41,4	8,4	5,6
6398,2	36,9	40,3	10,6	12,2
6398,25	41,5	40,4	8	10,1
6398,35	43,9	37,7	7,4	11
6398,42	44,3	41,9	11,3	2,4
6401,21	27,7	49,5	10	12,7
6401,24	33,8	45,9	9,2	11
6401,37	40	42,8	6,9	10,3
6401,43	32,3	46,2	8,2	13,2

6401,47	31,2	52,5	6,5	9,9
6401,58	41	40,4	9,9	8,8
6401,64	24,7	50,5	13,1	11,7