A study on Petrographic Analysis in Smart Water (SMW) EOR Flooding in a part of Oil field of Upper Assam Basin, India

Bhaskarjyoti Saikia#1, Minati Das*2

[1]*Department of Petroleum Engineering (DUIET), Dibrugarh University, Assam, India*

[2]*Department of Petroleum Technology, Dibrugarh University, Assam, India*

saikia6894bj@gmail.com

minatidas@yahoo.com

Abstract:

Thorough analysis of Petrographic studies dictates the behaviour of reservoir in understanding the characteristics which further helps in enhancing oil recovery. Clay minerals play an important role in Smart Water Flooding EOR process as it supports some of the major EOR mechanisms like Multiple Ion Exchange (MIE), cation exchange and fine migration during flooding operations. The present study is based on analysis of different petrographic studies like thin section analysis, XRD analysis, SEM analysis and to evaluate the impact on EOR process in a part of oil field of Naharkotia oilfield of Upper Assam Basin, India. Thin section analysis reveals the presence of different clayey and non-clayey materials present in the study area. Due to unique nature of clay minerals with negatively charged take part in exchanging cations during flooding thus disturbing the crude oil-brine-rock (COBR) interaction. The change in COBR equilibrium leads to change in wettability of the reservoir from oil/mixed wet to water wet hence increase in oil recovery. The XRD and SEM analysis show the different types of clay minerals, its texture and occurrence in the rock matrix of the study area. Swelling clays like montmorillonites get hydrated during SMW injection divert the injection fluid into unswept areas hence increase the microscopic displacement efficiency. The presence of non-swelling clays like kaolinite and illite adsorb crude oil onto its surface, making the reservoir oil/mixed wet. During SMW flooding, fine migration takes place in the reservoir that carry out the oil bearing clay minerals along with the smart water thus changing the wettability of the reservoir. The present study reveals the presence of different clayey as well as non-clayey minerals in the study area which supports the different SMW EOR mechanism thus enhancing oil recovery efficiency.

Key Words: **Clay minerals, Smartwater, COBR interaction, Wettability, Waterflooding**

Introduction:

Due to rapid industrialisation, the demand for crude oil has been increasing day by day. Many researchers have been carried out research on different enhanced oil recovery (EOR) methods to increase oil recovery. Smart Water flooding (SMW) is a relatively new environment friendly chemical EOR technique of tuning the ionic composition of the injected brine to change the wettability of reservoir rocks [1]. Different clay minerals in reservoir rock have an immense role in establishing equilibrium in crude oil-brine-rock (COBR) interaction. Compositionally sandstone is the most abundant with clay minerals and most of the pore spaces are contributed by the different clay minerals. During accumulation and migration, both authigenic and allogenic clay minerals hold hydrocarbon fluids by adsorbing them onto the surfaces in the reservoir. The major physical and chemical properties of clay minerals like adsorption, flocculation and cation exchange capacity (CEC) can be directly correlated with enhancing oil recovery technique [2].

It is crucial to understand the behaviour of different clays present in the reservoir because of two special properties namely CEC and Clay Swelling. Different clay minerals have different cation exchange capacity [3]. Mainly due to the dissociation of hydroxyl ions, clay minerals are found to be negatively charged [4]. These negatively charged sites attract cations to the clay surface where weak bonds can be established. During SMW flooding, cations can readily be exchanged for other cations as a result of low bonding strength. Because of their ability to exchange cations adsorbed to the external surfaces and the layers of the clay structure, clay minerals are often referred to as cation exchange materials [5]. The relative affinity to the clay surface of cations is referred to as the replacing power of the different cations in solution, which in room temperature is given as: [**6**]

$$\mathbf{Li^+ < Na^+ < K^+ < Mg^{2+} < Ca^{2+} < Sr^{2+} < Ba^{2+} << H^+}$$

The replacing power of cations is depends on relative concentrations of two cations. Hydrogen is active towards the clay surface due to very low concentrations. Different clay minerals in the reservoir have different cationic exchange capacity. Amongst all clay minerals, Montmorillonite has the highest CEC (70–150 meq/100gm) while kaolinite with lowest value of CEC (3-15 meq/100gm) [6**, 7**]. The CEC value of clay minerals is strongly dependent on the composition of rocks. The minerals like silica in sandstones are negatively charged at certain range of pH of the formation water [3]. They are good adsorbent of polar organic compounds in crude oil. As mentioned earlier, clay minerals are negatively charged particles by nature and act as cation exchanger during smart water flooding. The following figure (Fig 1) shows the adorption of crude oil onto the clay surface through polar organic compounds present in the crude oil [14].

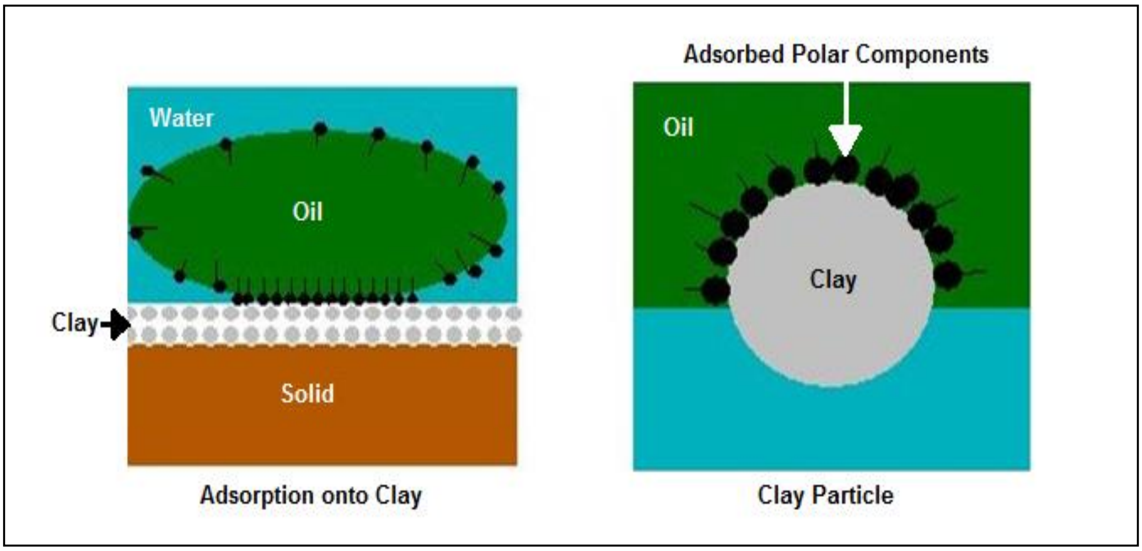

Fig 1: Adsorption of polar compounds on clay minerals

As mentioned, the another very important properties of clay minerals is Clay Swelling which proceeds via the migration of counterions that are initially bound to the mineral surface where they become fully hydrated during flooding. The extent of clay swelling strongly depends on the type of clay minerals and the affinity towards relative charges of ions. For instance, K^+ containing clays show a lower tendency to swell than Na^+ containing ones, whereas the reverse is true for Li^+ containing smectites. Though the clay swelling reduces the reservoir permeability but simultaneously it enhances sweep efficiency by diverting the fluid flow through secondary pores **[8].** Practically, it is very clear that any swelling behaviour will not contribute positively to the reservoir quality hence should be avoided [9].

Entrapment of hydrocarbon fluids has been found to be largely correlated to the presence of clays in the intergranular space in the reservoir. It has been well established that kaolinites are preferentially wetted by oil while illite and other clay minerals are wetted by water in oil-saturated sandstones [10]. Different researchers in their thermodynamic behaviour studies on clay minerals have found that adsorption of crude oil by clay minerals is a surface phenomenon and no chemical reactions involved between them [11]. Due to this surface adsorption, SMW flooding accelerates desorption of such adsorbed oil particles from the clay surfaces (migration of fines) thus increasing sweep efficiency and the entire process involves only on the surface of the clay grains.

The presence of clay minerals in the sedimentary rocks has an impact on wettability as it is related to the presence of polar organic compounds mainly resins and asphaltenes present in crude oil in the reservoir [12]. Petroleum researchers have observed that change in wettability in sedimentary rocks is largely correlated to the presence of clay minerals mainly illite and kaolinite in the reservoir rock's intergranular space. kaolinite preferentially adsorbs oil imparting it's hydrophobic characteristics to the mineral surface [13]. Adsorption of polar organic compounds of crude oil onto the clay minerals is dependent mostly on pH, brine composition, temperature and types of clay minerals.

The hydrophilic as well as hydrophobic character of illite and kaolinite in reservoir rock are dependent on adsorption of polar organic compounds on rock surface. As a result of adsorption of polar compounds on clay surfaces, the reservoir becomes more oil wet. Studies have shown that clay minerals such as kaolinite and illite contribute to the wetting properties of reservoir rock. The wettability property of the reservoir is mostly dependent on the types of clay minerals, ion binding and their adsorption capacity to hold the polar organic compounds of crude oil onto the clay surface. The presence of cations mainly divalent cations such as Ca^{2+} and Mg^{2+} in the formation brine acts as a bridge between oil components and the negatively charged clay minerals [15]. The ion binding mechanism mainly provides the opportunity for negatively charged carboxylates to alter the wetting conditions to less water-wet. Ion binding mechanism is probably the dominant wetting mechanism in wetting alteration in sandstone reservoirs during smart water flooding [16].

Keeping these in mind, the present study has been carried out for qualitative analysis of reservoir rock to identify the presence of different clay and non-clayey minerals, its different types and texture for evaluation of their role in carrying out SMW EOR flooding, in a part of oil field of Upper Assam, India

Materials and Methods:

For this study, 03 conventional core samples from Brail Formation of the study area have been collected from Oil India Limited, Duliajan. The characteristics of the core samples are given table (Table-1) below:

Table 1: Characteristics of the Core Samples of the Study Area

Sl Nos.	Samples	Depth Range(m)	Length, cm	Diameter, cm
1	CORE-1	2707.60 – 2707.83	23	7.9
2	CORE-2	3064.50 – 3064.72	22	8.1
3	CORE-3	3076.15 – 3076.36	21	8.0

While preparing CORE plugs, core cuttings have been separated and used for making samples for petrographic analysis. In the Agate Mortar, core cuttings were grinded and screened through 230 micron screen and powdery material have been used in thin section analysis. In thin section analysis, Leica DM 750P with Leica camera DMC2900 microscope has been used. For XRD analysis, core cuttings have been grinded and screened through 200 micron screen. The powdery materials with 74micron particle size have been used XRD Analyser, Model No RIGAKU ULTIMA-IV, Japan. For SEM Analysis, JEOL-JSM IT-300, Japan Analyser has been used for taking photographs.

Experimental Works

(1) Thin Section Analysis

Thin section microscopic figure (Fig: 2 – 5) reveals that the sandstones are moderately sorted and texturally matured. Most of the grains are subangular to subrounded, medium to fine grained having long, sutured, concavo-convex contact and point contact in some cases. This also showed the presence of detrital minerals, authigenic minerals and a few unidentified constituents. The detrital constituents present in the study area are mainly quartz, feldspar, rock fragments, mica, clay mineral also carbonaceous materials of different shape and sizes. Authigenic minerals, mostly clays which grew after deposition of sediments, i.e., during diagenesis, occur as a coating over the detrital grains and also within the fractures. The most troublesome authigenic mineral is smectite which occurs as pore lining materials [17, 18]. Its presence greatly increases the ratio of pore surface area to pore volume hence irreducible water saturation.

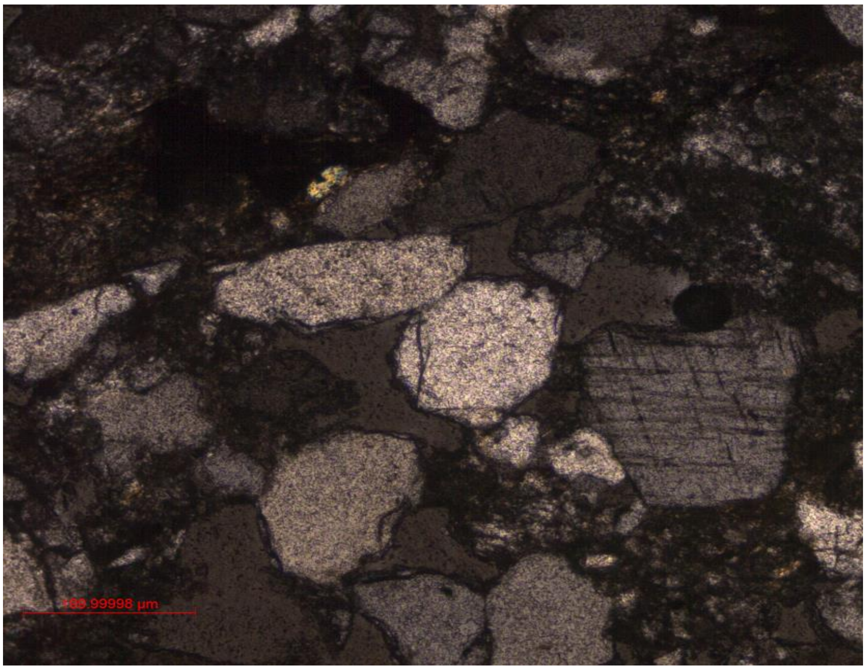

Fig2: Line contact under plane polarised light (Depth: 3064.53m)

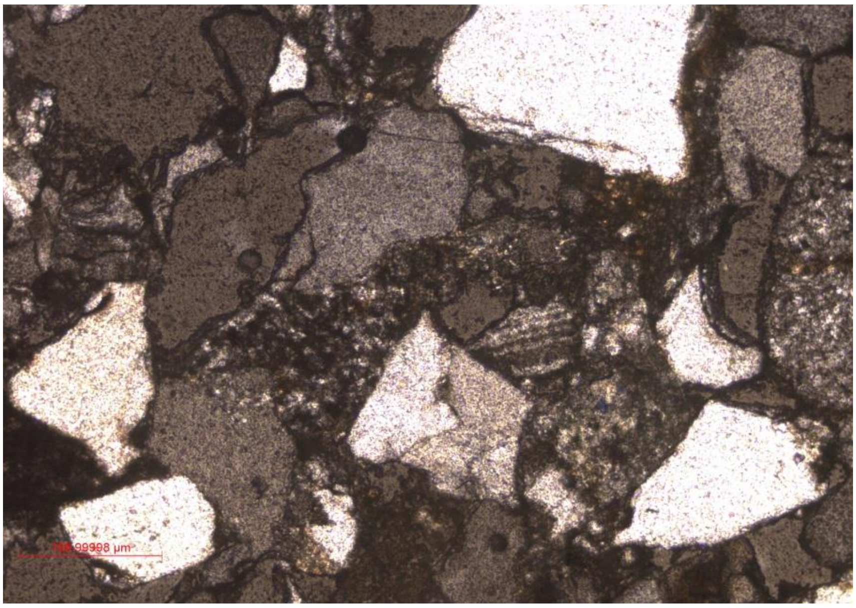

Fig3: Quartz, matrix, plagioclase feldspar, chert (depth: 2076.38m)

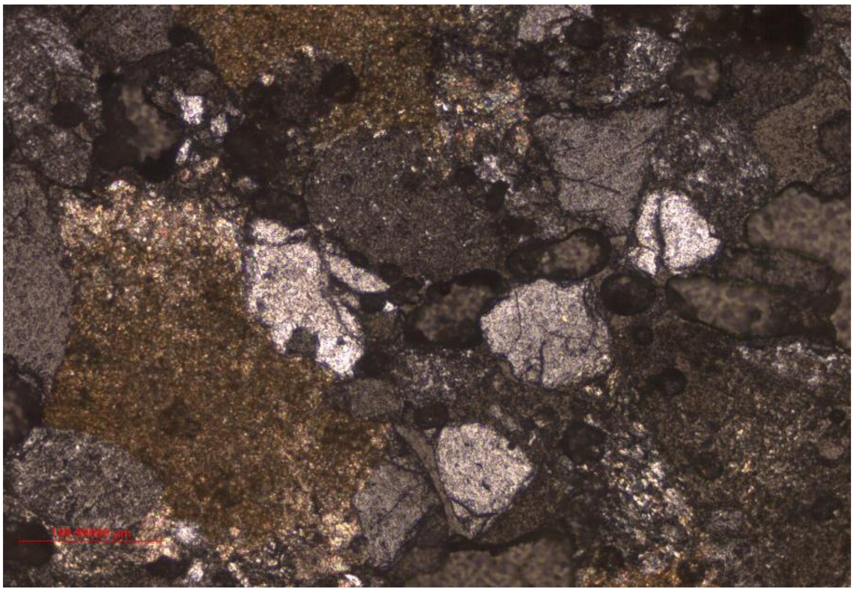

Fig4: Clayey material patches typically observed on Barail formation (Depth: 3064.28m)

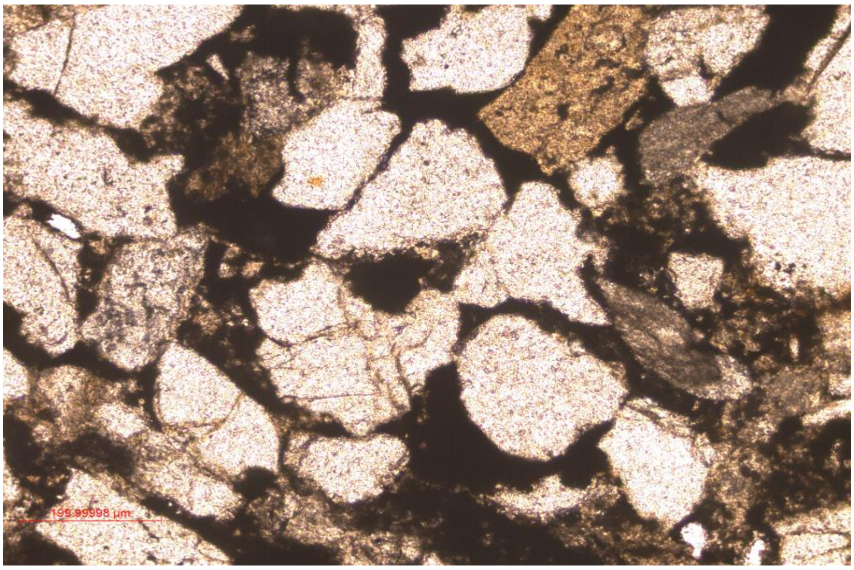

Fig5: Ferrugenous material observed, getting over in quartz grain (Depth: 3064.86m)

(2)XRD Analysis

It shows the different peaks corresponding to different clay minerals as well as non-clay minerals present in the study area (Fig: 6 - 7). Comparison of the unknown peaks is made with the set of standard pattern of peaks for different minerals. With the help of Standard Caroll, 1972 tables, the relative abundance of clay minerals was determined and selected the criteria set by Biscaye, 1965 [19, 20]. This analysis reveals the most abundance clay mineral in the study area is Kaolinite [$Al_2Si_2O_5(OH)_4$]. Other non-clayey minerals found in the study area are illite, quartz, mica, feldspar etc.

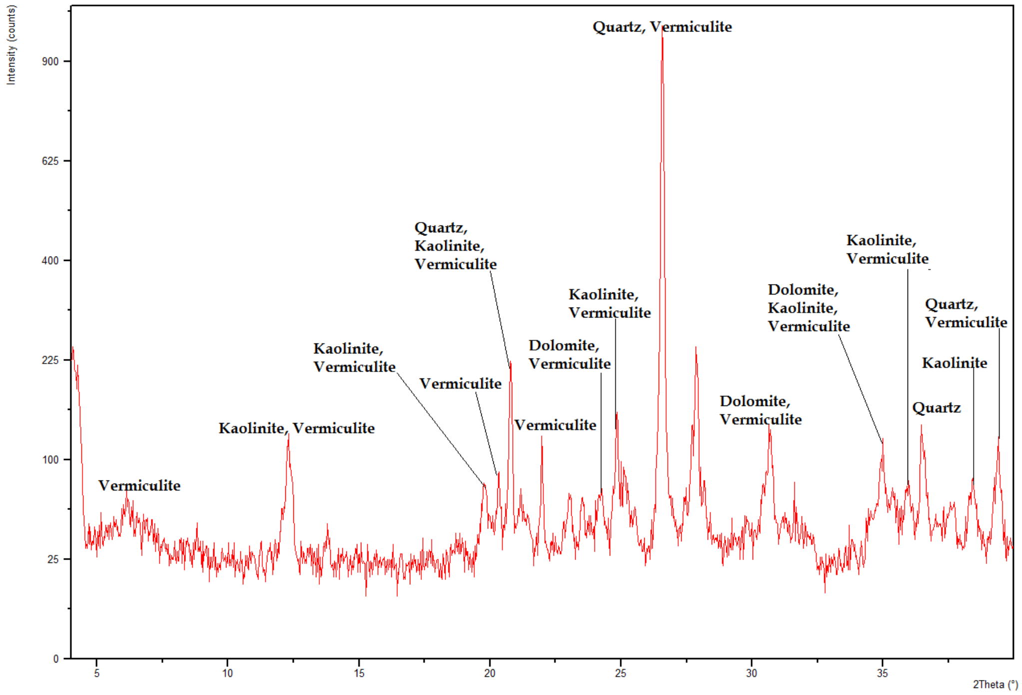

Fig6: XRD of sample having depth 3076.36m

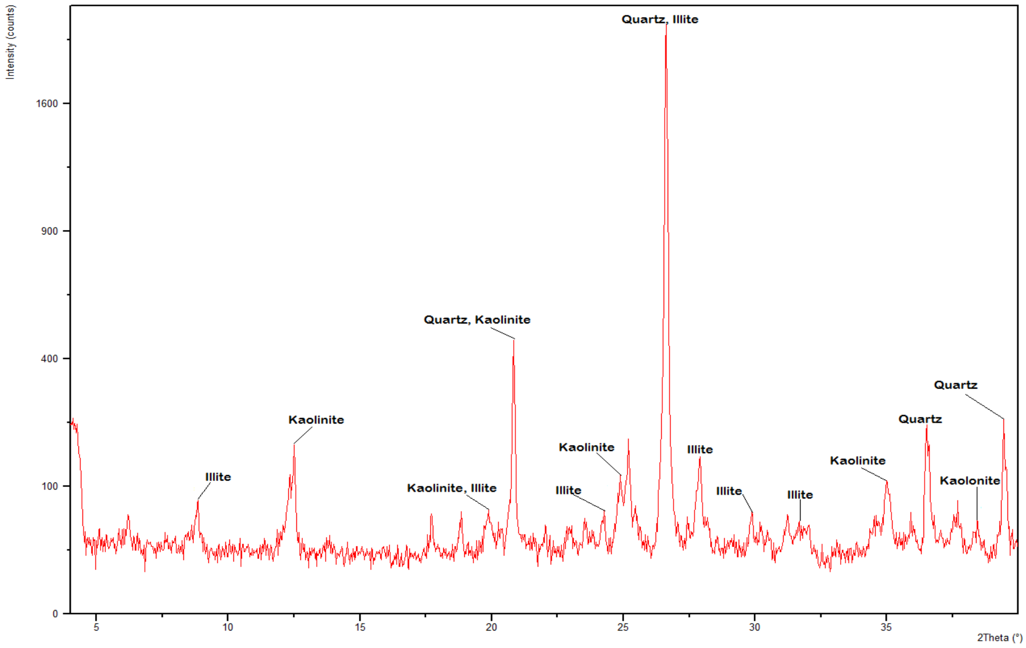

Fig7: XRD of sample having depth 3064.63m

(3)SEM Analysis

It reveals the dispersion of individual clay minerals as matrix in the pore spaces (Fig: 8 – 9). The SEM photographs also indicate permeable channels in the pore matrix of the sandstone. The wavy texture of the clay minerals combined with non-clayey minerals has also been observed in the photographs of SEM analysis. Intergranular pore spaces are somewhere partially blocked with clayey minerals like montmorillonite etc which are very much responsible for reducing permeability during in invading SMW for EOR process (Fig 8). The presence of most abundant kaolinite has been observed as stacked layers in the SEM analysis (Fig 9). As mentioned earlier, kaolinite clay plays an important role in migration on fines which leads to detachment of acidic and basic components of crude oil that were previously attached with clay surfaces [21]. So, kaolinite clay is one of the prerequisite for enhancing oil recovery during SMW flooding as mentioned earlier. The spiny projection of clay minerals in wavy textures has also observed in the analysis (Fig 8). Thus, SEM analysis dictates the textures, occurrence, nature of clayey as well as non-clayey minerals, coating materials etc.

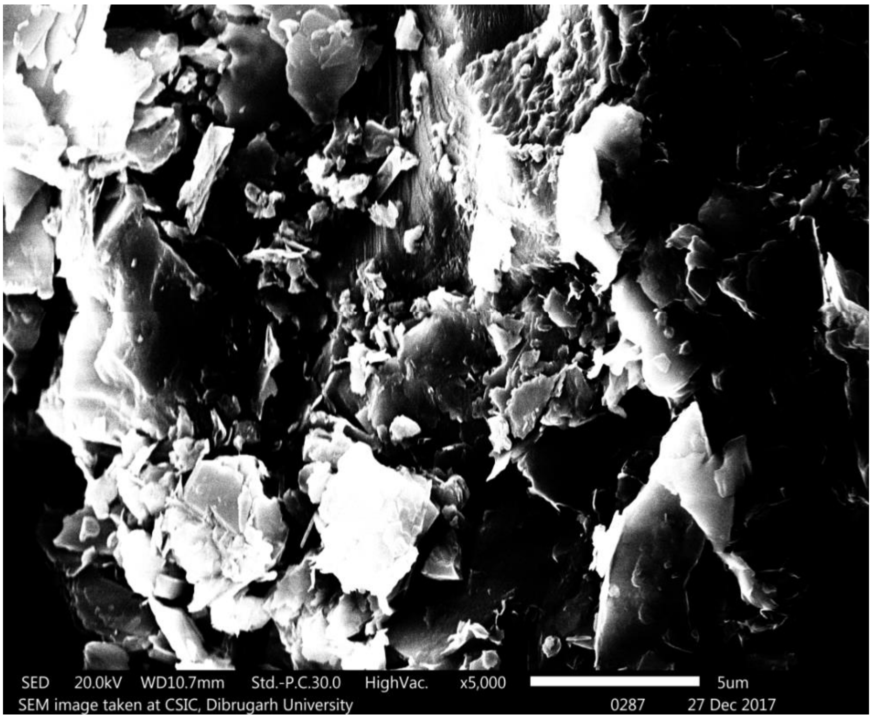

Fig8: SEM photograph reveals the presence of smectitie with honeycomb nature of sample having depth 2707.50m

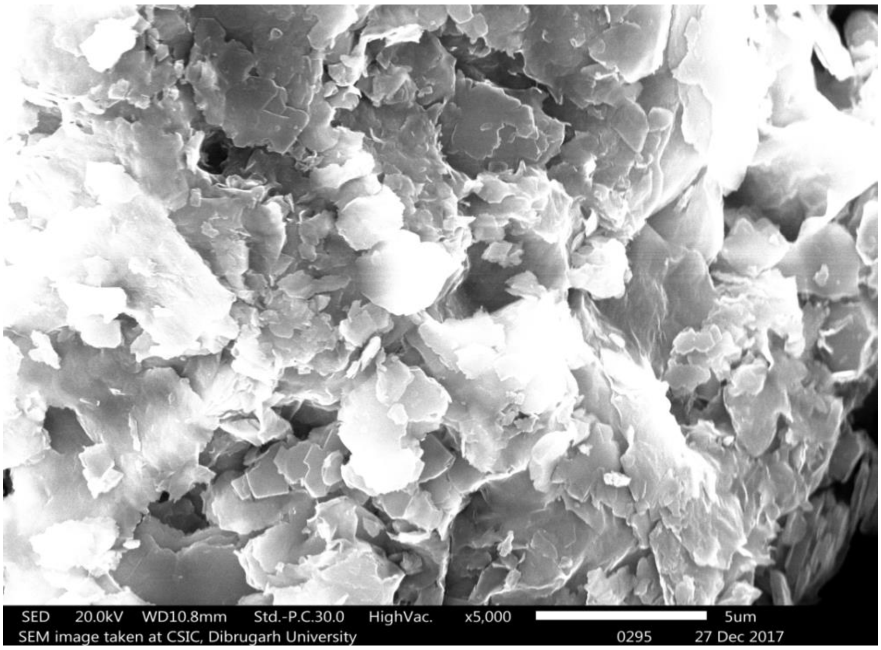

Fig9: SEM photograph of sample having depth 3076.54m shows the presence of kaolinite and illite with platey nature

Discussion

Researchers have been found that clay minerals have a greater impact in developing brown oilfields. As mentioned earlier, presence of different clay minerals is a very important prerequisite to carry out SMW flooding to improve oil recovery. In the thin section studies, clay minerals along with other non-clayey constituents have been observed. To identify the types of different clay minerals, XRD analysis has been done which ascertained the presence of clay minerals like kaolinite, muscovite, illite in the study area. Besides these clay minerals, quartz, feldspar, mica are also observed in the sample. Finally, Scanning Electron Microscope (SEM) analysis has been done to show the details of clay mineral textures along with the coating patterns of rock matrix.

As pointed out earlier, two factors are important regarding clay minerals in rock matrix: firstly, presence clay minerals and secondly role of different clay minerals in SMW EOR processes. All the above mentioned petrographic studies have shown that the rock matrix is enriched with clay minerals indicating suitability of the study area to carry out further EOR processes. Both swelling and non-swelling clays have significant role in displacing oil from the pores. Once swelling clays become hydrated due to application of smart water, it starts swelling and simultaneously reducing the pore throat in the rock matrix thus contributing reduction in permeability. On the other hand, blocking of pores restricts the fluid flow and diverts it to upswept areas within the pores. Apparently, swelling clays reduces the fluid permeability but it enhances the sweep efficiency by diverting fluid to unswept areas.

Presence of clay minerals also supports the multiple Ion Exchange (MIE) mechanism which is also one of the established mechanisms to support SMW process [14, 22]. It is being mentioned earlier that clays are unique for it's negatively charged in nature. The negative charge will contribute to change in wettability modification to more water-wet. Once SMW is injected into the reservoir, ion exchange will take place between different cations with organo-metallic compounds in crude oil originally attached with clay minerals. The importance of clay minerals is that it supports the MIE mechanism by detaching the complex ions from the clay surfaces by altering COBR equilibrium that leads to wettability alteration. Another very important role of clay minerals is that it increases local pH of the injection brine due to exchange of H^+ ions with the cations which were previously adsorbed in MIE mechanism. This increase in pH due to cation-cation exchange is another factor for alteration of wettability to more water wet state thus improving oil recovery [3, 23].

Presence of non-clayey minerals like kaolinite can be correlated with wettability of the reservoir rock. During accumulation and migration of hydrocarbons, kaolinite adsorbs oil on their surface thus makes the reservoir oil wet. Change in wettability from oil to water wet happens due to migration of kaolinite fines with oil attached with it during injection of smart water [24]. Further they observed the partial reduction of permeability due to blockage of some pore spaces by migrated fines of kaolinite. This movement of fines lead to increase of recovery efficiency as it carries oil laden fines during SMW flooding.

CONCLUSION

Based on the petrographic study, the authors inferred the following conclusions:

(i) Sandstones of the study area are mostly abundant with clayey minerals like illite, kaolinite, vermiculite etc also non-clayey materials like quartz, different forms of feldspar, mica etc.

(ii) Presence of non-swelling clay minerals mainly kaolinite supports migration of fines during SMW flooding as mentioned earlier researchers.

(iii) Presence of different clayey minerals in the study area reveal the suitability of the field to support cation exchange mechanism as the clay minerals are negatively charged in nature. This cation exchange mechanism is linked with change in wettability of reservoir rock towards more water wet hence enhancing oil recovery.

(iv) Also observed complex textures of clay minerals in the rock matrix with thick coating materials over detrital grains that lead to reduction of permeability and porosity.

(v) Presence of swelling clays indicates that reduction in permeability would happen due to injection of smart water during flooding as it will get hydrated. Apparently, this leads to reduction in permeability of reservoir rock matrix but on the otherhand it enhances microscopic displacement efficiency by diverting injected water into unswept areas.

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