New insights into the application of a magnetic field to enhance oil recovery (EOR) from oil-wet carbonate reservoirs

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ABSTRACT: Given recent moves towards cleaner energy production, the application of environmentally friendly methods for EOR is considered to be an important research strategy in increasing oil production from existing hydrocarbon reservoirs. Therefore, in this paper, the application of a magnetic field is introduced for the first time as a novel and eco-friendly EOR technique for oil-wet carbonate reservoirs.

The magnetic field is generated using three different magnet strengths of 3000, 4100 and 6000 Gauss (G). The impact of incremental increases in magnetic field on oil production from Austin chalk is investigated through measurements of contact angle, rock compaction and the spontaneous imbibition of water and the monitoring of rock surface streaming potential.

Dynamic contact angle measurements on oil-wet chalk surfaces in the presence of a magnetic field show that the value of contact angle is reduced faster than when a magnetic field is absent, indicating a significant increase in water imbibition into rock pores. The results of spontaneous imbibition tests reveal significantly greater oil production during the imbibition process in the presence of a magnetic field at about 8.5 times that from oil-wet chalk.

Monitoring of the streaming potential of the oil-wet rock surface in the presence and absence of a magnetic field indicates that a change in surface potential charge is responsible for the change in wettability of the surface from oil-wet to water-wet, hence improving water imbibition into carbonate rock which, in turn, can improve the oil displacement from pores.

Keywords. EOR, Magnetic field, Wettability alteration, Streaming potential, Carbonate rock

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1 INTRODUCTION

Nearly two-thirds of the world's daily oil production is accomplished by using the technique of enhanced oil recovery from oil wells which have already passed their peak production capacities[1]. The most common techniques used for EOR are gas injection, chemical flooding and thermal methods[2,3]. Several researchers have reported low recovery factors from carbonate reservoirs during water flooding due to the low spontaneous imbibition of water into the low permeability matrix [4]. The low imbibition of water into carbonate rocks is mainly attributed to the fact that most carbonate reservoirs are oil-wet oil[5]. This condition becomes worse if natural fractures exist in the rock system where water is diverted to the fractures, hence bypassing significant oil volumes behind the water front. To solve this issue, several EOR methods such as smart water flooding, low salinity water flooding, water-alternating gas injection, polymer flooding, surfactant flooding and the use of nanoparticles may be adopted to overcome problems of water imbibition into the rock matrix[6–14]. Long payback periods, costly water treatment, the compatibility of water with rock surfaces, and low injectivity are among the problems encountered when using these methods.

It has been proven that the chemistry of water has a pronounced effect on oil recovery due to alterations in the surface charge of the rock known as the zeta potential[15,16] . This is an important parameter in the control of electrostatic interactions between active layers and particles at the interfaces, hence affecting surface wettability[17,18]. The electrokinetic process affects the electric charges at both the carbonate/brine and oil/brine interfaces, which in turn influence the adsorption/desorption of polar components in crude oil on/from rock surfaces. This process eventually alters the wettability[19] of the rock towards being water-wet. Therefore, the design of the composition of water for flooding requires knowledge of the zeta potential of interfaces. If the chemical composition of water yields a zeta potential with the same polarity at the interfaces, repulsive forces will stabilize the water film on the surface and cause an increase in oil recovery[20]. The levels of rock surface forces are dictated by the presence of ions determining surface potential. For instance, for carbonate rock, the potential determining ions are Ca^{2+} and CO_3^{2-}. Carbonate rock has a positive surface charge when the sum of Ca^{2+} and CO_3^{2-} ions is positive and a negative surface charge when the sum is negative. Any chemical reactions on the surface which cause an imbalance in the ions on the surface result in changes in surface forces, and hence the flow of fluids in pores is affected. Seawater contains ions that have the ability to cause an imbalance in the ion concentration of the carbonate rock surface, which can alter the wetting conditions[21]. For instance, sulphate ions in seawater with high affinity towards calcite ions are considered to have strong potential to modify the ions on the calcite surface[22]. This in turn affects the adsorption/desorption of polar components onto/from the rock surface[23]. The change in rock surface potential charge eventually influences oil production as it has a direct impact on water imbibition into the rock matrix.

Recently, several eco-friendly techniques such as the application of magnetic fields and the use of electromagnetic (EM) waves have been proposed for the enhancement of oil recovery from reservoir rock[24–26] utilizing nanoparticles synthesized for EOR, where an increase in oil recovery is observed when a magnetic field is applied. In one study[27] , the process was tested by passing water through a magnetic field. The results showed that the time taken for the breakthrough event is shortened with an increasing level of magnetism in water. EM waves have also been used in a thermal method to improve enhanced oil recovery using electromagnetic waves emitted by a curve transmitter[24]. The recovery factor was found to increase by 43.71 % and 59.26 % for the two core samples utilized in core flooding tests. Dielectric nanofluids have also been injected into the oil reservoir with simultaneous electromagnetic irradiation[26], leading to increased oil recovery by creating disturbances at the oil-water interfaces and greater sweep efficiency. A combined electrocoagulation and magnetic field has also been introduced to enhance marine lightweight oil spill recovery with less energy consumption, and it was found that demulsification is enhanced by applying permanent magnets within the electrocoagulation reactor[28]. Recently the new nanoparticle solutions of citric acid-coated magnetite nanoparticles has been tested by researchers using a micromodel for enhanced oil production [29]. It was found that the nanoparticles responded to the magnetic field was at around 800 G, and the maximum oil recovery was found at an intensity of 2750 G. The impact of different strengths of magnetic field on the interfacial tension of a cationic surfactant as an emulsifying agent has been studied for its ability to improve the performance of conventional water flooding[30] . It was found that there was a slight increase in the IFT of oil/nanoemulsion, which resulted in increased oil recovery. Moreover, the application of magnetic fields has been extended to the flow and heat transfer aspects of coal-fired Magnetohydrodynamic (MHD) generators in the presence of a porous medium, where enhanced flow has been reported along with a buoyancy effect and heat generation[31].

Even though the studies mentioned above show the importance of a magnetic field for oil recovery from different types of reservoir, no work has been reported for carbonate rock. Therefore, in this work, we investigated for the first time the application of a magnetic field as an innovative technique for enhanced oil recovery from oil-wet carbonate rock. Three different magnetic strengths of 3000 G, 4100 G, and 6000 G were used. The effects of the magnetic field on the pH of the solution, the surface tension of the displacing fluid and the wettability of the rock surface are studied. Moreover, this paper presents data on the recovery factor (RF) for oil recovered from core samples during spontaneous imbibition in the presence and absence of a magnetic field. Zeta potential measurements for the rock samples are also included to support the proposed mechanisms.

2 Materials and Methods

2.1 Materials

The carbonate rock considered in this study is outcrop Austin chalk supplied by Kocurek Industries, Texas. The core plugs 1 inch in diameter were drilled. The range of their permeability was between 8-15 md, with a porosity of 25-27 %. Table 1 presents the physical properties of the core plugs used in this study.

Table 1. Core properties

Core No.	Diameter (mm)	Length (mm)	Dry weight (g)	Pore volume (PV)	Porosity %	Absolute Perm water (Kw) (md)	Swi %
Core #1	25.23	69.68	66.19	9.5	27.3	8.769	43.16
Core #2	24.94	72.16	70.58	9.49	27.4	9.48	31.81
Core #3	25.08	72.21	70.65	10.02	28	7.209	22.2
Core #4	25.10	70.3	67.22	9.41	27.04	9.48	22.42
Core #5	25.15	70.03	67.69	9.63	27.9	8.62	19
Core #6	25.15	70.34	69.2	9.75	27.17	7.021	35.38

Energy dispersive X-ray spectroscopy (EDX) was used to define the elemental composition of the chalk. Table 2 presents the EDX results for unmodified chalk. As can be seen from the table, the unmodified chalk contains 44.03 % of calcium and only 0.83 % of other metallic ions, and so all interactions between rock, oil, and water were expected to be dominated by calcium carbonate.

Table 2. Elemental composition of Austin chalk in percentage from EDX test

C	O	Mg	Al	Si	Ca	Fe
10.08	45.06	0.2	0.09	0.28	44.03	0.26

The synthesized seawater was prepared based on the Kester Seawater (SW) recipe[32]. The oil model for all tests was n-decane with 99% purity mixed with stearic acid of 90% purity supplied respectively by VWR UK and BDH Chemicals Ltd, Poole, England. To avoid the impact of the complexity of crude oil composition on wettability and ultimate oil recovery, n-decane was selected as a simple and single component to represent crude oil. Stearic acid is a long chain fatty acid used to represent polar components in crude oil. According to previous research[33], C_{18} carboxylic acid has high affinity towards carbonate rock, hence changing its wettability to oil-wet. To generate magnetic field in this work, three different strengths of neodymium magnet of 3000 G, 4100 G and 6000 G provided by First4Magnets were used.

2.2 Methods

2.2.1 Core preparation

The Austin chalk core plugs were cleaned using Toluene for 48h, and thereafter they were dried in a vacuum desiccator at 70° C. The dried cores were kept under vacuum for 48 h to remove air trapped in the pores. The deionized water was sucked into the core plug with breaking vacuum. To make sure that water had entered all pores, including the smaller ones, a hydraulic pressure of 500 psi was applied to the core samples for 3hrs. After releasing the hydraulic pressure, the water-saturated plugs were kept under saturation without pressure for approximately 8-10h. The absolute water permeability of all samples was then measured at room temperature. The fully saturated samples were flooded with 1.5 PV of model oil to establish initial/irreducible water saturation.

After core flooding, the core plugs were aged in 0.01M stearic acid solution in n-decane for 30 days at 40°C.

2.2.2. Spontaneous Imbibition

The spontaneous imbibition (SI) of water into both oil-wet and water-wet samples at room temperature was determined using an Amott Cell. To quantify the impact of the magnet field on the oil recovery factor from core samples during SI, a magnet belt was installed on the Amott Cell as shown in Fig.1. The experimental set-up for SI test is as below:

- Exposure time to the magnetic field:30 days
- Core plug mass varied from sample to samples as shown in Table 1.
- Conductivity values of the DW and SW were 1µS/cm and 54000µS/cm respectively
- Temperature: 21^{0}C.

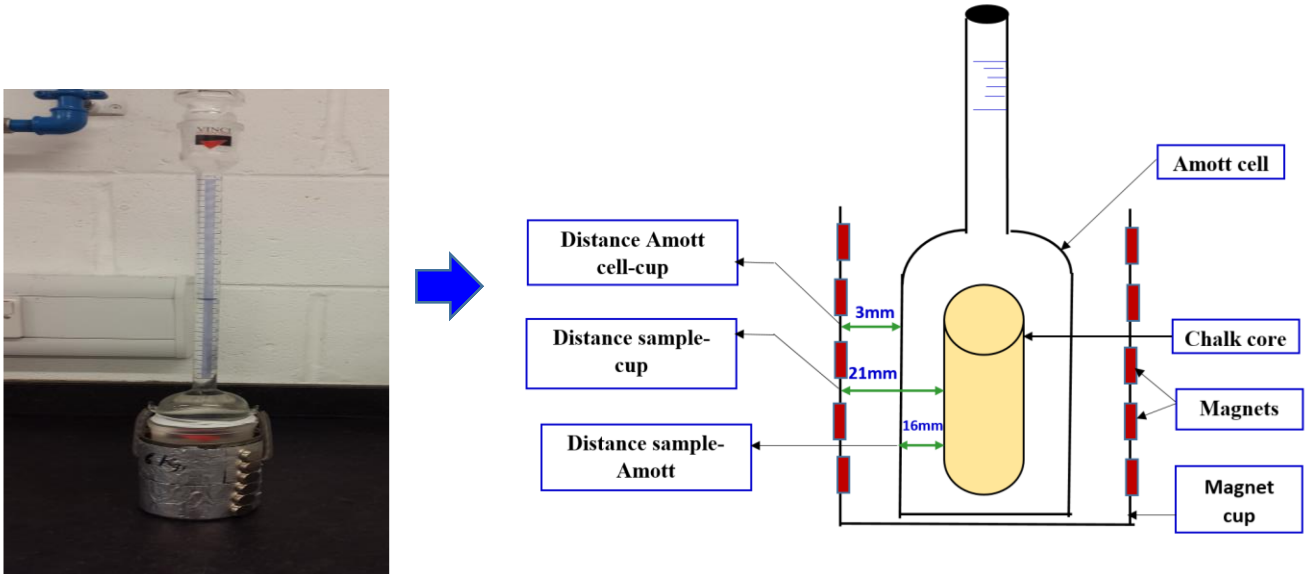


Figure 1. Amott Cell with magnet belt

The surface tension and pH of displacing fluid (deionized water (DW) or seawater (SW)) before and after contact with the core samples were measured using a tensiometer K9 Kruss GMBH and Hanna pH probe respectively. At the end of the SI process, the core samples were dried, crushed and sieved before quantifying their wettability using measurements of contact angle and surface charge analysis.

2.2.3. Contact angle measurement

Contact angle measurements were performed on solid discs or prepared pellets made from the crushed chalk core samples. The discs were prepared by cutting the core samples using a diamond saw with denoised water as cooling fluid. The discs were then washed with deionized water and dried in the oven at 70°C for 24hrs prior to contact angle measurements. The pellets, on the other hand, were prepared from crushed chalk by pressing about 1 gram of solid sample, which had previously been aged and dried, using hydraulic press equipment (SPECAC, England). A force equivalent to approximately 9 tonnes was applied for 150 seconds to ensure the uniform morphology of the pelleted surface. The uniformity of pelleted samples was checked by the calculation of sample porosity using scanning electron microscopy (SEM) images, where two prepared pellet samples using the aforementioned approach have similar porosity. Dewinter Material Plus software was used to analyze the surfaces in terms of sample porosity on the basis of images taken from SEM. Fig. 2 shows two examples of these images and their corresponding porosities calculated prior to the contact angle measurements.

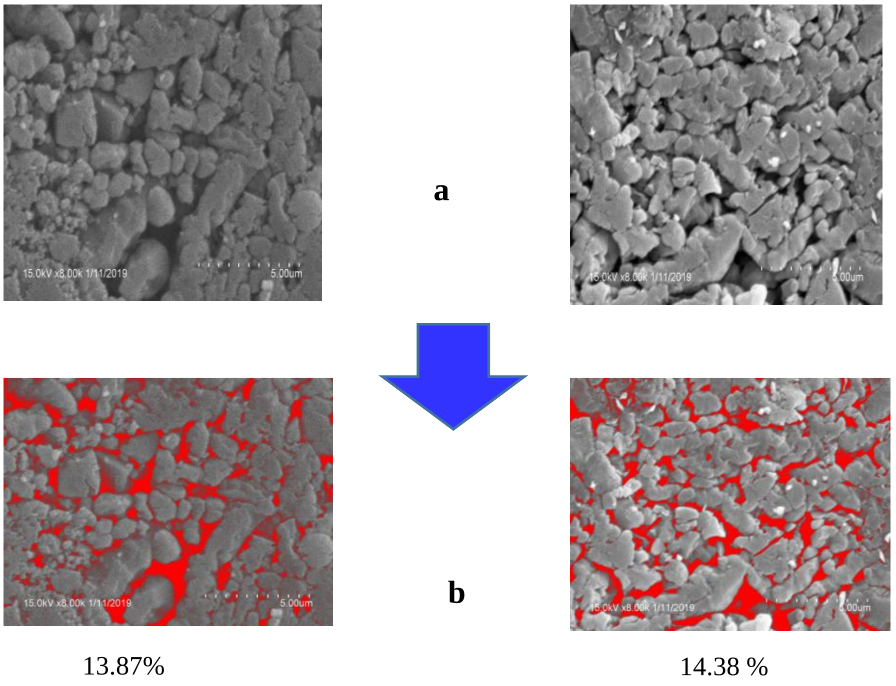


Figure 2. SEM images (a) and images taken from Dewinter Material Plus for pelleted chalk samples illustrating pores in red (b).

Contact angles on the pelleted samples were then measured using a Kruss DSA 100 goniometer (Germany). Deionized water droplets were placed on the flat surface of the solid discs using a syringe with a micrometric screw. Images of the water droplets placed on the disc surface were immediately recorded using Kruss data acquisition software and the contact angle (CA) was automatically determined. In order to study the impact of the magnetic field on contact angle, a magnetic belt was built and installed around the solid disc in accordance with the selected magnetic strengths of 3000 and 6000 G (16 magnets for each). Fig .3 shows the set-up for contact angle measurement. Various experimental details are summarized as follows:

- Exposure time to magnetic field: The exposure time varies from 23 to 60 min depending on strength of magnets where higher strength required lesser exposure time.
- The mass of the pellets was approximately 1g while that of discs was 14 g.
- Thickness of the disc was approximately 17mm.
- Temperature: 21^0C.
- Water droplets used for contact angle measurements: double-distilled water (ddH_2O) with a conductivity of 0.05 µS/cm.

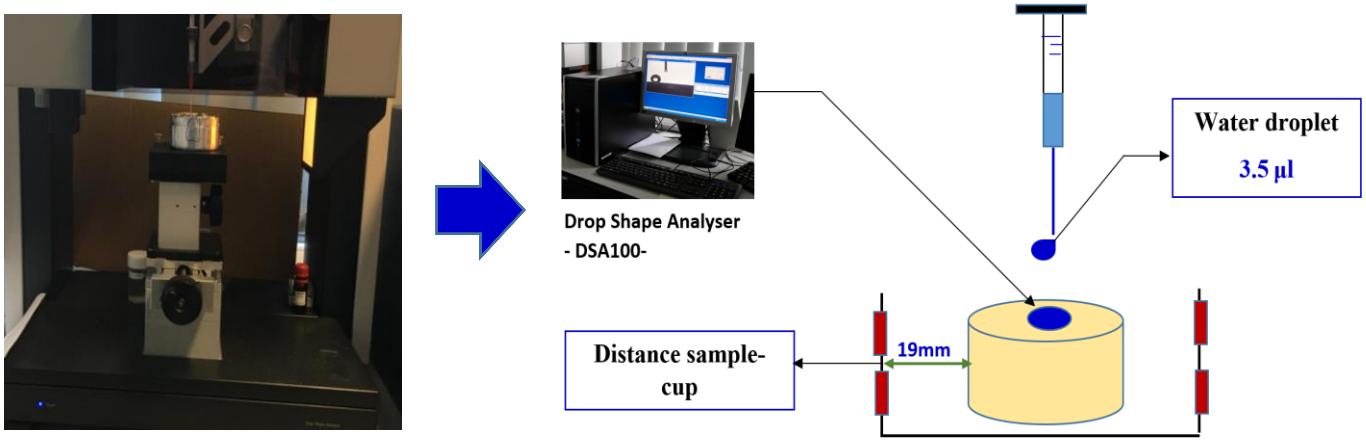


Figure 3. Contact angle experimental set-up

It is worth mentioning that three measurements were conducted for every disc or pellet, and three pellets/discs were prepared for every sample, giving a total of nine measurements. The final value for contact angle reported in this paper is the mean of these 9 measurements.

2.2.4 Zeta potential measurements

The zeta potential (ZP) was determined by a Sur Pass electrokinetic analyzer (Anton Paar, UK) at room temperature. Two types of measurement were performed on the samples. The first was used to investigate the direct impact of the magnet on surface potential by installing magnet belts on the sample holder of the zeta analyzer device (6 magnets for each strength of 3000 G and 6000 G); and the second to investigate the impact of the magnet on the surface potential of the sample during the imbibition process, during which no modification to the zeta analyzer device was required.

3 RESULTS AND DISCUSSION

In this work, the impact of a magnetic field was first studied in terms of the contact angle and zeta potential of modified and unmodified rock samples. Its impact was then evaluated based on oil recovery during the imbibition process using DW and SW as displacing fluids.

3.1. Impact of magnetic field on dynamic contact angle measurement

Contact angle measurements on modified chalk show an initial value of 122 degrees, indicating an oil-wet surface. The contact angle was recorded over time with and without the presence of a magnetic field and the results are presented in Fig. 4 and Table 3. As can be seen from the results, the imbibition of water into oil-wet chalk is slower in the absence of a magnetic field. For instance, the change in the recorded contact angle on the oil-wet chalk surface from 122±0.5 to 91±0.1 degrees takes 51 minutes in the absence of a magnetic field; however, it takes only 32 minutes in the presence of a magnetic field generated by a 3000 G magnet (48000 G in total). Further enhancements in imbibition were observed when the magnetic field was increased with a 6000 G (96000 G in total) magnet where, for the same reduction in contact angle, only about 17 minutes was required. This observation is illustrated clearly in Table 3 where the magnets are shown to speed up water imbibition into the oil-wet samples. It is worth mentioning that the change in wettability using a magnet is temporary and, when the magnetic field was removed, the behaviour of the surface returned to that when oil-wet in the absence of a magnet. These results show that the wettability of chalk rock can be controlled by a magnetic field, hence imbibition of water into the matrix. The fact that water moves faster in porous media in the presence of a magnetic field has been already reported by *Hashemizadeh et al* [27]. However, they concluded that exposing water to a magnetic field reduces its viscosity, leading to its faster movement in porous media, which in turn results in early water breakthrough so that therefore the recovery factor is reduced with increasing magnetic field strength.

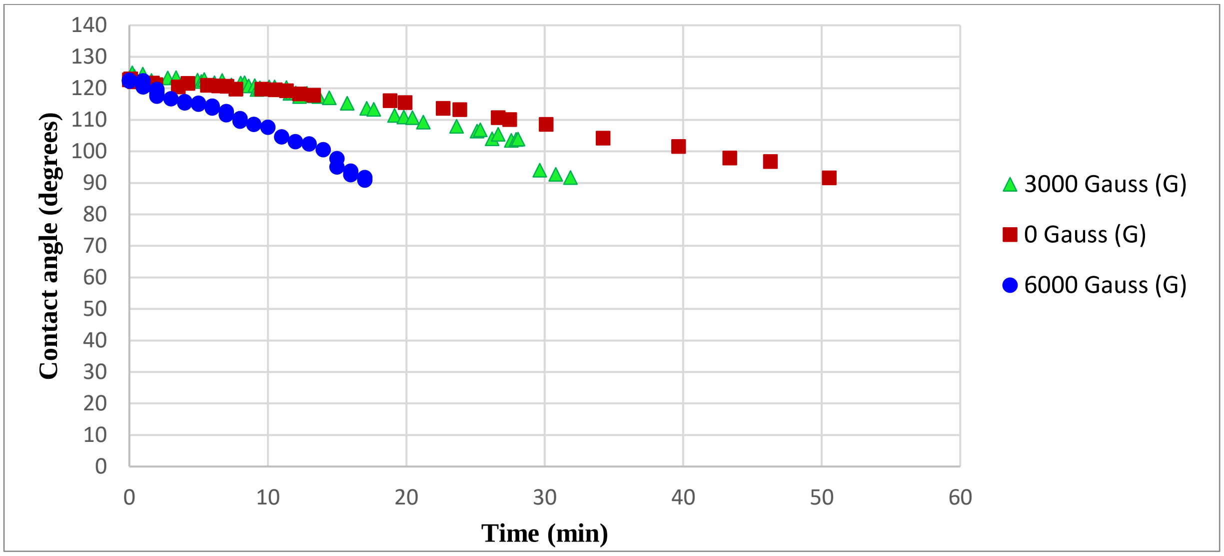


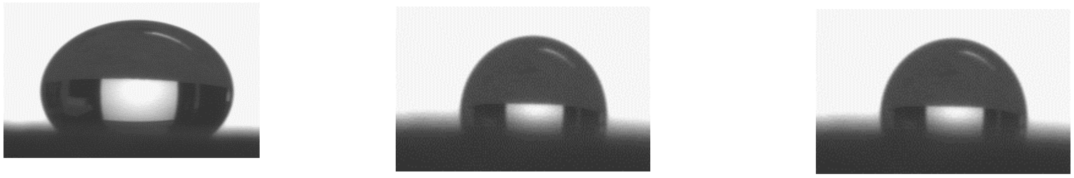
Figure 4. Water imbibition into oil-wet samples illustrated in terms of measured contact angle on chalk disc in the presence and absence of magnets with different strengths

Table 3. Time dependency of contact angle measurement on oil-wet chalk disc in the presence or absence of a magnetic field

Sample	Time (min)	Contact angle (degrees)	Δ Time (min)
Oil-wet chalk 0 G	0	122.7	
	27	110.7	27
	51	91.6	24
	60	63.2	9
Oil-wet chalk 48000 G	0	123.3	
	20	110.7	20
	32	91.7	12
	41	60	9
Oil-wet chalk 96000 G	0	122.6	
	8	110.4	8
	17	91.7	9
	23	59.2	6

Fig. 5 presents images of water droplets on oil-wet chalk disc surfaces corresponding to the contact angle data shown in Fig. 4 and Table 3. The volume of water droplet for all experiments is 3.5 μl. As can be seen from Fig. 5, the water droplet becomes flat in a shorter period of time in the presence of 6000 G than that for 3000 G and in the absence of a magnet. Similar results have been reported previously[34], where it was found that in the case of water based magnetic, there is a decrease in the height and increase in the width of droplets. It can be clearly seen from the images that the drops become flatter with time due to the effect of the magnetic field. Their heights decrease and their widths increase, leading to greater adherence of the water to the surface.

Moreover, it has been demonstrated that the profile of the droplet can be expanded in the presence of a downward magnetic force which decreases the contact angle, and *vice versa* when an upward magnetic force is applied[35]. Another study has demonstrated that adding magnetic particles to Sn-Zn solder decreases the contact angle[36]. A very early study on this topic[37] showed that surface tension maintains the spherical shape of the droplet, and it deforms when it is subjected to an electrical or magnetic field. This deformation depends on properties such as the permittivity, conductivity and permeability of rock surfaces.

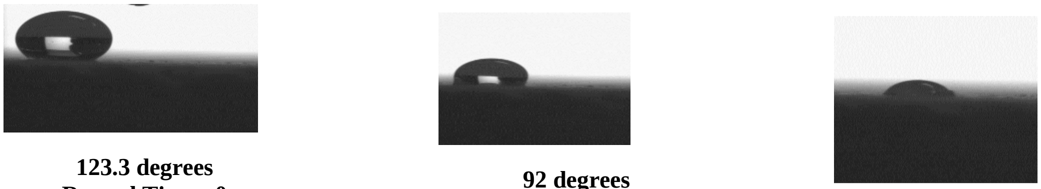


122.7 degrees
Record Time =0

94.7 degrees
Record Time =48 min

63.2 degrees
Record Time = 55 min

a. Aged core 0 Gauss (G)



123.3 degrees
Record Time =0

92 degrees
Record Time = 32 min

60 degrees
Record Time = 42min

b. Aged core 48000 Gauss (G)

121.8 degrees
Record Time =0

92.9 degrees
Record Time =15

59.2 degrees
Record Time = 24

c. Aged core 96000 Gauss (G)

Figure 5. Effect of magnets on water droplets on oil-wet chalk discs.

3.2. Impact of magnetic field on chalk streaming surface potential

To investigate the real impact of a magnetic field on the characterization of the chalk surface, the streaming potential of oil-wet chalk surfaces in the presence and absence of a magnetic field was measured using the zeta analyzer and the results are presented in Fig. 6**.** It is clear that increasing magnet strength will change the zeta potential towards less negative values. For instance, the zeta value of modified chalk (aged core) was -24.14 mV. After adding 3000 G and 6000 G magnets with a total of 6 magnets each, the values changed to less negative values of -23.63 mV and -21.12 mV respectively. In addition, it was observed that after removing the magnets the zeta value returned to its original value of -24.14 mV. Hence, the effect of magnets was temporary, as with the effect observed for contact angle measurements presented in Table 3.

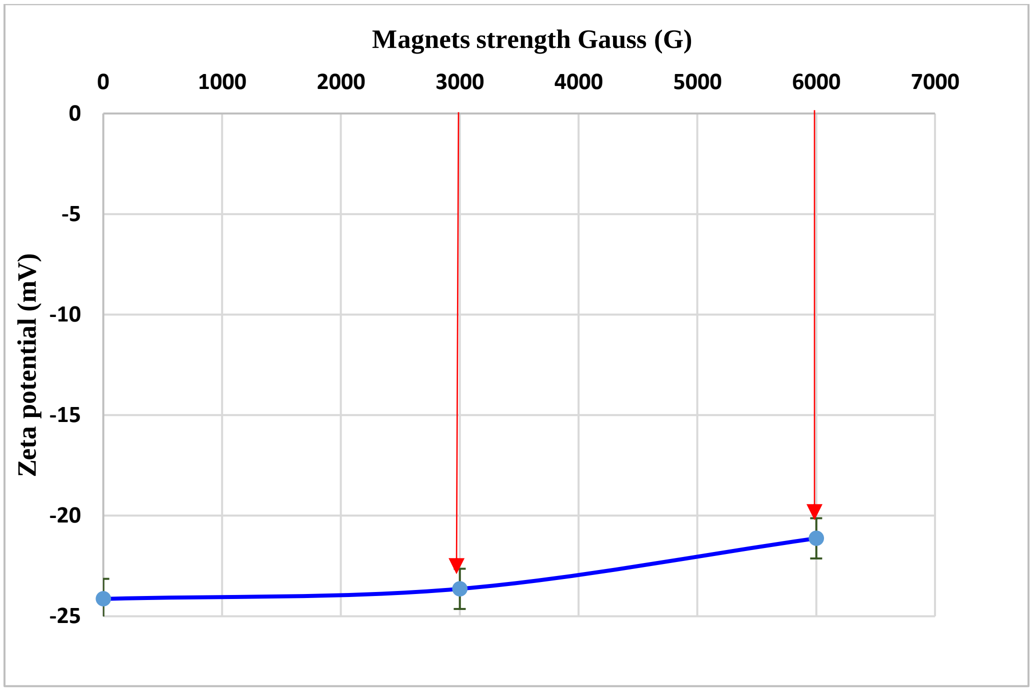


Figure 6. Effect of magnets on zeta potential of oil-wet chalk

In a subsequent trial, the impact of the magnetic field on the chalk surface before and after the imbibition process was measured using the zeta analyzer. Table 4 compares the contact angle and zeta potential results for unmodified chalk samples before imbibition and for the same samples imbibed with DW in the presence of a magnetic field. These results indicate rock surface modification towards being more water-wet. A previous study investigated the effect of exposure to magnets on the zeta potential of polystyrene latex particles in electrolyte solutions[38], and it was found that the zeta potential becomes less negative in a magnetized solution, which accords with our findings.

Table 4. Measured contact angle on pelleted chalk and zeta potential data for the same samples in the presence and absence of a magnetic field using DW as displacing fluid.

Cores	Contact angles (degrees)	Zeta potential (mV)
Unmodified chalk (water-wet)	45	-19.09
Core 2: Unmodified chalk imbibed with DW in presence of magnetic field	10.2	-15.22

As can be seen from this table, the initial zeta potential of unmodified chalk has a negative value of -19.09 mV corresponding to the measured contact angle of 45 degrees. After spontaneous imbibition with DW the contact angle declined to 10.2 degrees and the zeta potential increased to -15.22 mV. Thus the wetting state changed from being weakly to strongly water-wet.

3.3 Impact of magnetic field on oil production

To evaluate the impact of a magnetic field on oil production from water-wet and oil-wet chalk samples, spontaneous imbibition tests using a modified Amott cell were conducted.

3.3.1. Oil production from water-wet samples in the presence and absence of a magnetic field

It is well known that oil recovery from water-wet rocks during the water flooding process is easier than from oil-wet rocks[39–41]. When the rock is water-wet, water can imbibe into it and oil is displaced from the pores without significant resistance due to the capillary effect. In this study, the impact of a magnetic field has been studied for both water-wet and oil-wet rock samples.

Fig. 7 and Fig. 8 show the calculated oil recovery factors for water-wet samples during the imbibition process using deionized water as the displacing fluid. Fig. 7 presents the results for the case where the magnetic field was added to the system at the end of spontaneous imbibition and oil production from the core sample was continued up to its ultimate recovery, while Fig. 8 shows the results for the case where magnetic field was applied from the start of the imbibition process.

As can be seen from Fig. 7, the recovery factor for core#1 in the absence of a magnetic field reached its ultimate value of 26.27 % after a short period of time of 200 hrs. For core#2, the magnetic field was applied in 3 steps. In the first step, the magnetic field generated by 3000 G magnet strength was added to the system after the core sample had reached ultimate recovery. It is observed that the oil recovery factor increased by 8.34%. In the second and third steps, the magnet strength was increased to 4100 G and then 6000 G, which resulted in extra oil recovery of 2.77% and 2.78% respectively. The significant increase in oil production of about 13.89% over the three steps shows that the magnetic field enhances the imbibition process, and hence oil displacement. Recent work[25] has shown that the application of electromagnetic waves and magnetic fields during ferrofluid flooding increased the oil recovery factor by approximately 10.33%. In contrast, no enhancement of production during water flooding was observed in another study[27] in the presence of strongly and weakly magnetic water, and the recovery factor was approximately the same compared to with normal water. The authors explained that, with the increase in the magnetic field, a reduction in the viscosity of water was observed which resulted in early water breakthrough and hence no enhancement in production was achieved.

Applying the magnetic field from the start of imbibition yields a drastic increase in oil recovery in a short period of time, as indicated in Fig. 8. It can be seen that the incremental production levels due to the application of the magnetic field generated by magnet strengths of 3000 G, 4100 G and 6000 G were 21.39 %, 8.55 % and 7.13 % respectively, which is almost double that observed when the magnetic field was applied later during the imbibition process. Hence, adding magnets at time 0 is recommended in order to achieve a higher recovery factor (RF %) in a shorter time.

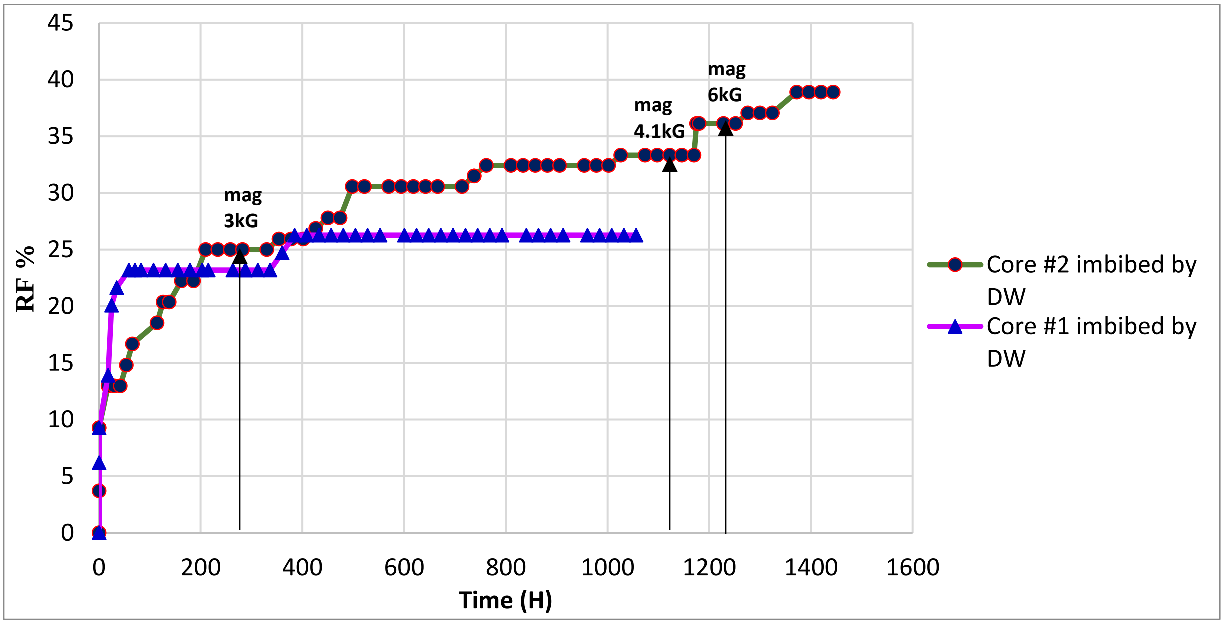


Figure 7. Effect of magnetic field on water-wet chalk when applied at the end of spontaneous imbibition

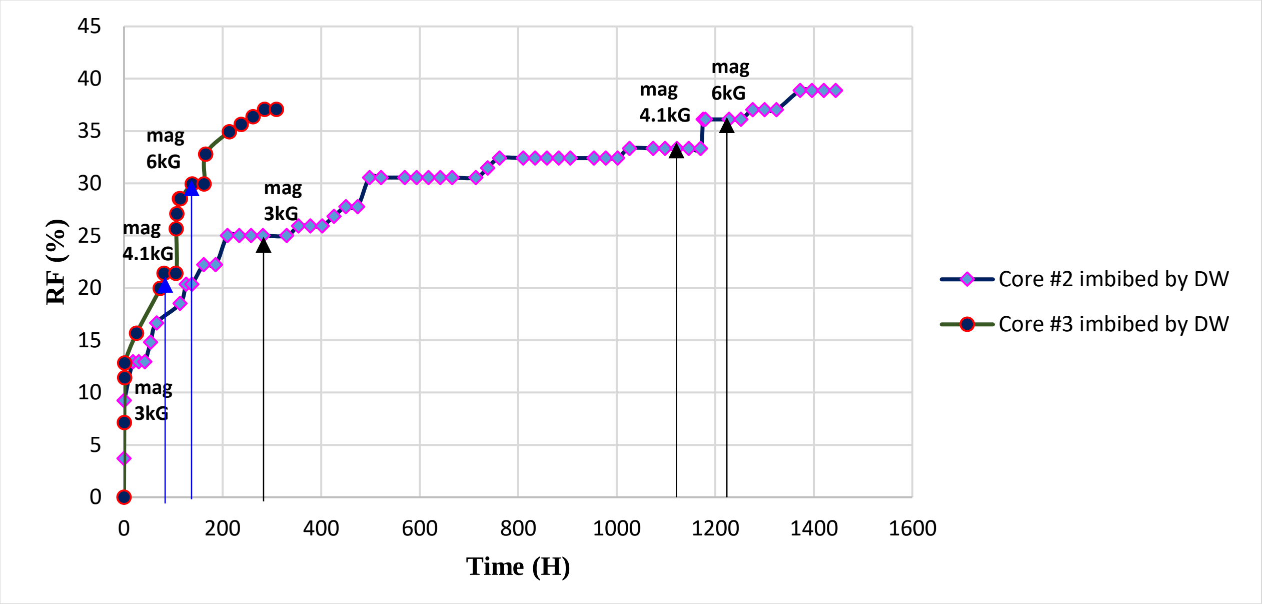


Figure 8. Effect of magnetic field on water-wet chalk when magnets added at time 0 min (at start of spontaneous imbibition)

3.3.2. Oil production from oil-wet samples in the presence and absence of a magnetic field

In contrast to water-wet samples, the level of oil recovery from oil-wet samples during spontaneous imbibition using deionized water as the imbibing fluid is 2.73 %, as shown in Fig. 9 where the ultimate oil recovery occurred during first few hours of production and no further production is observed for up to 400 hrs. Adding a magnetic field generated by 3000 G and 6000 G magnets into the system increased production by 2.74% and 1.01% respectively.

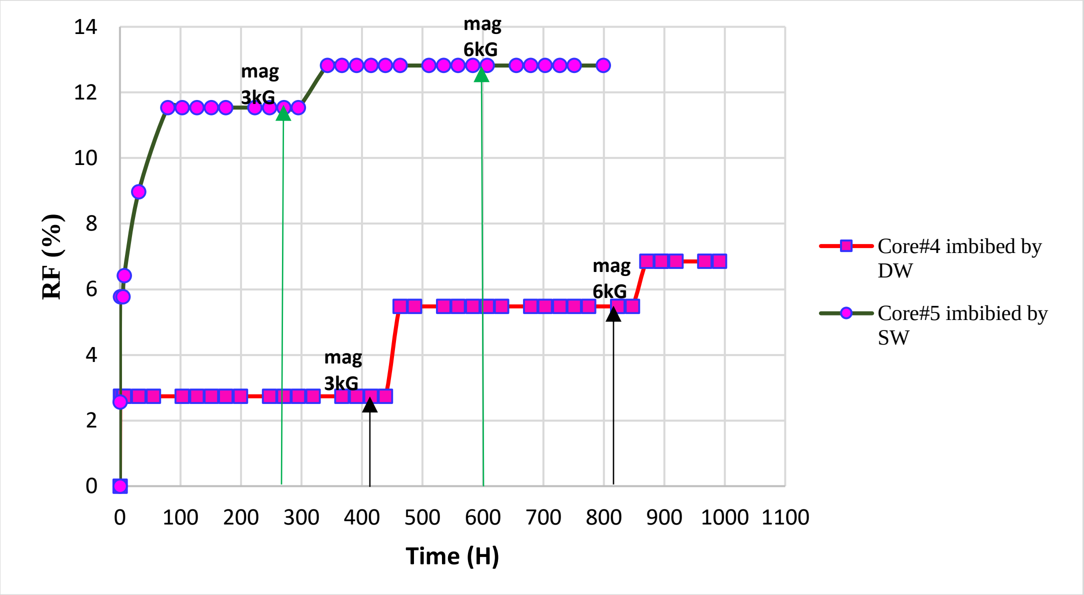


Figure 9. Effect of magnetic field on oil-wet chalk when applied at the end of spontaneous imbibition

Changing the displacing fluid from deionized water to seawater affected the oil recovery from oil-wet samples significantly, where the initial production increased to 11.53 %. The results are presented in Fig. 9. This observation is in line with the previous research[25] where significant improvements in oil recovery from coreflooding were achieved after adding a magnetic field to ferrofluid (Fe_2O_3) dispersed in seawater. Including a magnetic field generated by a magnet strength of 3000 G gives about 1.29% extra oil recovery but no additional production was observed with 6000 G. These results show that the magnetic field is more effective in deionized water, with an incremental oil recovery of 3.75% compared to that of sea-water for oil-wet chalk.

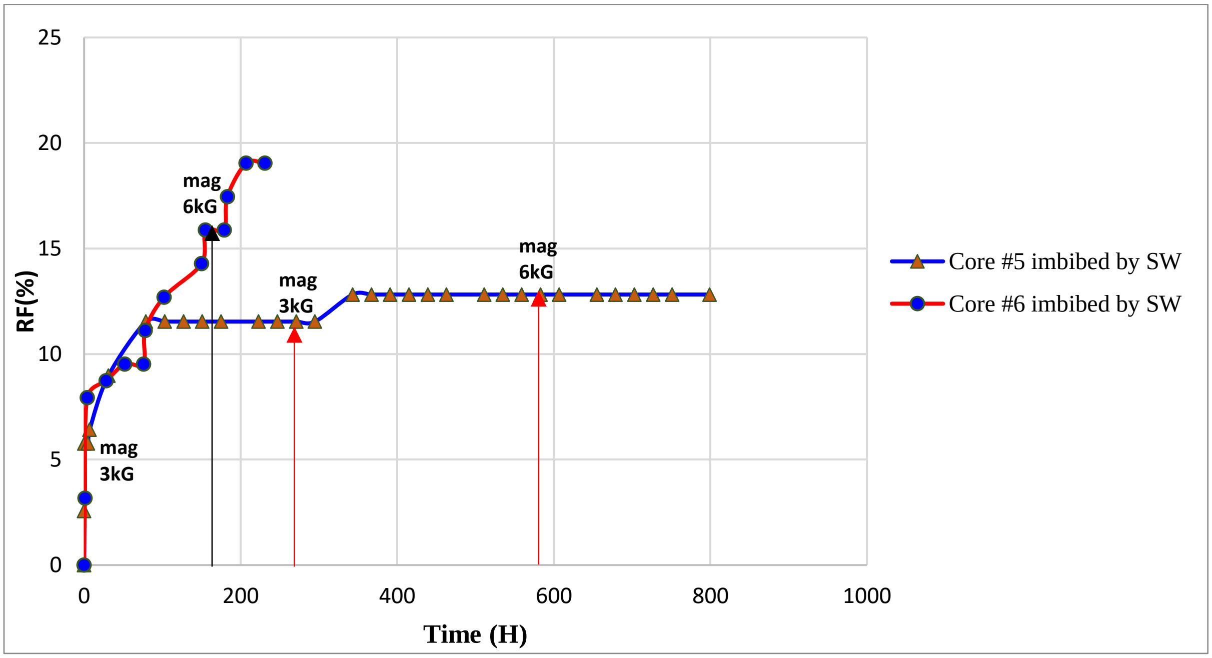


Figure 10. Effect of magnets on oil-wet system when magnets added at time 0 min. (at start of spontaneous imbibition)**.**

For water samples with imbibition by deionized water, it is observed that the inclusion of the magnetic field from the start of the imbibition process was more effective, where it is associated with a significant increase in oil production. Similar behaviour was also observed for oil-wet samples imbibed by sea water. Fig. 10 presents the recovery factors for the inclusion of magnets at the start of the imbibition process. As can be seen in this figure, the magnetic field speeds up production where, for instance, the oil recovery factors for a magnetic field generated by magnet strengths of 3000 G and 6000 G reached 15.87%, and 19.04% respectively. The total production is about 15% higher than that of production from oil-wet samples imbibed by deionized water in the absence of a magnetic field. The use of seawater-assisted magnets seems to be a promising approach to release oil from oil-wet carbonate rock. A summary of oil production levels from all samples is given in Table 5.

Table 5. Summary of values of oil recovery factor (%) during the spontaneous imbibition process using DW (deionized water) or SW (seawater) as displacing fluids for all samples in the presence and absence of a magnetic field.

Core No. and wetting condition Imbibing fluid		Total recovery factor (RF %)	Incremental oil production (RF%) from magnetic field
Core 1: reference core - water-wet	DW	26.27	
Core 2: Water-wet	DW	25	
	DW+3000 G	33.33	8.33
	DW+4100 G	36.11	2.78
	DW+6000 G	38.89	2.78
Core 3: Water-wet	3000 G/DW	21.39	
	4100 G/DW	29.94	8.55
	6000 G/DW	37.07	7.13
Core 4:Oil-wet	DW	2.73	
	DW+3000 G	5.47	2.74
	DW+ 6000 G	6.84	1.37
Core 5: Oil-wet	SW	11.53	
	SW+3000 G	12.83	1.3
	SW+ 6000 G	12.83	0
Core 6 :Oil-wet	3000 G/SW	15.87	4.34
	6000 G/SW	19.04	3.17

3.3.3. Chemistry of water samples after the imbibition process

Table 6 presents results for the chemistry of the water at the end of the imbibition process for water-wet samples imbibed by deionized water in terms of pH and surface tension. As can be seen in this table, there is no change in pH from the start to the end of the imbibition process in the presence of a magnetic field generated by a magnetic belt with a total strength of 81000 G. These results prove that the enhancement in production due to the magnetic field cannot be attributed to changes in fluid chemistry, but instead is due to alterations in rock wettability and changes in its electric charge. These findings concerning pH and surface tension are in line with the results of a previous study where it was reported that a magnetic field with strengths ranging from 0 to 24,000 G did not cause any change in the pH of deionized water[42] .

Table 6. pH and surface tension measurements for water samples at the end of spontaneous imbibition process for water-wet samples imbibed by deionized water

Magnets	Time (hrs)	pH	Surface Tension (mN/m)
81000 G	0	7	63.73
	100	7.4	63.4

Moreover it has also been found[43,44] that the intensity of the magnetic field has to be high to be able to cause a reduction in surface tension, which confirms the reliability of our surface tension results. In summary, a magnetic field has the ability to alter the electric charges in favour of alterations in wettability towards being more water-wet without affecting the fluid chemistry of displacing fluids, hence increasing sweep efficiency by enhancing the displacement of oil by water.

CONCLUSIONS

In this work, laboratory experiments regarding the effect of magnets on oil recovery from carbonate rock have been conducted for the first time. The results are discussed based on alterations in the wettability of rock surfaces and surface rock streaming potential, as well as changes in the pH and surface tension of displacing fluid.

The results show that implementing a magnetic field during the imbibition process of water enhances oil recovery from both water-wet and oil-wet rocks where, for instance, for water-wet rock samples the oil recovery factor increased from 25 % to 38.9 % with corresponding increases for oil-wet rocks from 2.73 % to 6.84% using deionized water as the displacing fluid.

It is observed that changing the displacing fluid from deionized to seawater as well as including a magnetic field from the start of the spontaneous imbibition process resulted in significant increases in the amount of oil recovered, where oil recovery for oil-wet samples under these conditions increased by 19.04 %.

The contact angle measurements of water droplet on rock samples showed that samples in a magnetic field experienced a faster decline in contact angle over time than those without a magnetic field, hence leading to the faster imbibition of fluids into pore spaces. It is observed that, when the magnet strength was doubled, the imbibition time was approximately halved.

The examination of the chemistry of deionized water as displacing fluid in terms of changes in pH and surface tension during the imbibition process revealed that the magnetic field has no chemical effect and no changes in pH or surface tension were recorded during the process.

From the above observations, it may be concluded that the change in the wettability of the rock surface due to the presence of a magnetic field is the main driving mechanism for the enhancement of oil recovery in carbonate rock. The change in wettability can be also attributed to the change of electric charge on the rock surface. This was proved by measuring the streaming potential charge on the chalk surface in the presence and absence of a magnetic field.

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Notes

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