Mineralogy Identification In Reservoir Rock Samples Using Low And High Field Magnetic Susceptibility Measurements On Synthetic Samples

Alfitouri I. Jellah

Abstract: The magnetic susceptibility signal is one of the important properties on minerals that can be used to identify these minerals and distinguish them from each other as different minerals have different magnetic susceptibility readings and response. Minerals according to their magnetic response are classified to three main categories: Diamagnetic, Paramagnetic, and Ferrimagnetic which are commonly present in the hydrocarbon reservoir and some of them are considered to be important controlling factors for some of the reservoirs properties related closely to the capability of these reservoirs to contain hydrocarbons flow in the porous media and then its production to the production wells. Examples of these properties are permeability and microporosity which showed very good correlation with the magnetic susceptibility measurements particularly those that have been taken at high applied magnetic field.

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Introduction

The scope of this work is to identify the presence of various minerals and their relative concentrations in the samples using Low and high field magnetic susceptibility measurements. For this, two devices (MS2 B & VFBT) provided by the Institute of petroleum engineering, HWU, were used to investigate the magnetic susceptibility analysis of synthetic samples made of Illite clay and matrix minerals such as quartz (Illite is an important permeability controlling mineral in North Sea reservoirs). Low and high field magnetic susceptibility measurements were taken on these synthetic samples. The experimental data were compared with the model magnetic plots for various concentrations of Illite clay in a quartz matrix. A known concentration of magnetite was introduced in the above synthetic samples in order to investigate the response of these three minerals mixture at low and high applied fields to model the real life samples where more than one magnetic minerals can be present. Conclusion of this work has been provided as well as future work recommendations.Potter (2005) used low field magnetic susceptibility measurements to characterize minerals; components in reservoir samples. In (2006), together with Ivakhnenko; he extended this work and detailed how magnetic hysteresis and remanence measurements could be used for improved , rapid, non-destructive characterisation of multiple mineral (and fluid) components in reservoir sample by acquiring data at range of low and high applied fields. In (2007); they described a systematic theatrical and experimental magnetic analysis of different clay types for reservoir characterisation. In this work they first produced plots of different clays in quartz matrix and then they undertook some experimental measurements on a series of synthetic reservoir samples comprising various concentrations of clays in quartz matrix for comparison. Arfan & Potter (2009), presented a methodology using low and high field magnetic susceptibility measurements to quantify the relative roles of Illite clay and hematite on the permeability of red and white reservoir sandstone samples when observed that in many clastic reservoirs containing both red and white sandstone formations, the permeability is lower in the red sandstones. They have investigated thermomagnetic analyses of magnetic susceptibility in these sandstones in tight gas reservoirs and concluded that there was not much change in magnetic susceptibility in red sandstones with temperature increase on the opposite of that of the white sandstones which decreased with temperature.

Equipment & Methodology

To measure the magnetic susceptibility at low field; seven syntactic samples were prepared with different concentrations of quartz and illite varying from 100% quartz to 100% illite as shown in Table 2. MS2 B dual frequency device shown in Figure 4 was used to conduct this set of experiments. This device is designed to conduct low magnetic field experiments on soil or rock samples and it accepts 10ml and 20ml cylindrical bottles shown in Figure 4. It also accepts 1'' diameter core plug. A manually operated platen allows the sample to be inserted and positioned centrally within the sample cavity. A calibration sample with low temperature and frequency dependency is supplied with the sensor. Dual frequency cross calibration is quickly accomplished with the use of the calibration sample and adjuster tool. The theatrical magnetic susceptibility was calculated for each sample using values of 0.6 & 15X10-8 m3 kg-1 for 100% quartz and illite respectively9. The MS2 B is considered as a portable laboratory sensor as it has facilities of making measurements at two different frequencies which allow the identification of an important class of very fine ferrimagnetic minerals described as superparamagnetic, found commonly on soils and in some rocks. When using low susceptibility measurements; the total magnetic susceptibility of all the components in the sample including the Paramagnetic, Diamagnetic, Ferri-and Ferromagnetic minerals is obtained. The advantage of the low field magnetic susceptibility measurements is that they are very rapid and non-destructive and can be applied at a range of

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- *Alfitouri I. Jellah*
  Institute of Petroleum Engineering, Heriot-Watt University, Edinburgh, EH14 4AS, UK & Azzaytuna University. P. O. Box: 98339 Tripoli/Libya.

sample scales including whole or slabbed cores, core plugs, and cuttings and even on powders. However, the drawback of the low field measurements is that they are influenced by the presence of small amounts of ferri/ferromagnetic minerals. Since ferri/ferromagnetic minerals posses high magnetic susceptibility (much higher than paramagnetic and diamagnetic minerals), their presence overestimate the content of paramagnetic minerals if used the model equations described earlier. To compensate for their effect, we use high field magnetic susceptibility measurements using the VFTB kit shown in Figure 6. The high field slope of the hysteresis curve is representative of the content of Para/Diamagnetic minerals in the sample; whereas the low field hysteresis represents the presence of any ferromagnetic minerals in the samples (by the size of the kink). The size of the kink at low fields can be used to quantify the presence of any ferri/ferromagnetic minerals in the sample. On the other hand, when the sample contains pure diamagnetic material; the slope will be negative. On the other hand, paramagnetic minerals give positive slope, and the ferrimagnetic minerals also give positive slope at high applied field only. For creating the magnetic hysteresis curves, the same samples compacted very tightly; packed into a non-magnetic container and the Variable Field Translation Balance (VFTB) located in the petrophysics laboratory of the Heriot-Watt University. The VFTB system Figure 6 is a modification of the horizontal magnetic translation balance in which the magnetic gradient is created by a separate set of four gradient coils. The name ‘’variable‘’ came because that the magnetic field in this device is not constant but it is changing with a certain frequency. It has a horizontal translation balance in which the magnetisation of the sample is measured. The measurements can be made in fields up to 1000 mT10. The main advantage of the VFTB is that all the apparatus is computer controlled so that once the sample is in the measuring position, many experiments can be applied to the same sample. Thus a whole range of magnetic experiments can be carried out. The sample holder slides into the sleeve at the end of the balance assembly. The obtained data is processed using a software program VFTB Analyser, which allows mass correction for each sample as well as determination of magnetic properties. The results of the hysteresis measurements are presented in a form of plots of the applied magnetic field versus the magnetization which provide a universal template at which any mineral or reservoir rock can be identified. The high field slope of there plots indicates the presence of diamagnetic (negative) and paramagnetic (positive) minerals. The ferrimagnetic minerals con be recognized by the presence of a kink at the low field and the size of this kink corresponds to their concentration in the sample. Using the two devices at the Petrophysics Laboratory in Heriot-Watt University, the experiments were conducted in five stages as following: Low Field Magnetic Susceptibility Study on Diamagnetic & Paramagnetic Minerals (MS2 B). Low Field Magnetic Susceptibility Study on Diamagnetic & Paramagnetic plus Ferrimagnetic Minerals (MS2 B). Low & High Field Magnetic Hysteresis Study on

Results & Discussion

Low Field Magnetic Susceptibility Study on Diamagnetic & Paramagnetic Minerals

In this set of experiments; a number of synthetic samples were prepared in the petrophysics laboratory differing in minerals concentrations from 100% diamagnetic material represented by quarts to 90% quarts plus another paramagnetic material represented by Illite as shown in Table 1 below: From the results of the low field measurements shown in Table 2 and plotted in Figure 4; it can be noticed that as the percentage of Illite increases in the sample the slope shifts towards the positive which enables us to identify the components of any sample and the approximate concentration when we obtain similar shape. Furthermore, it can be seen that both the theoretical and experimental curves almost lay on each other which proves how representative the experiments on the syntactic samples are. These measurements have been used to quantify different minerals in reservoir rock samples such as clays which play an important role in controlling rocks permeability.

Low Field Magnetic Susceptibility Study on Diamagnetic & Paramagnetic plus Ferrimagnetic Minerals

A 0.1% of ferrimagnetic material was added to five of previously prepared samples and using the same device, low magnetic susceptibility measurements were taken and the results are summarized in Table 2 below: It can be clearly seen that when very small percentage of ferri-magnetic mineral represented by Magnetite (only 0.1%) was introduced to the sample; very big shift was occurred to the curve which can be seen in Figure 5. The presence of such impurities in the reservoir rocks can affect the interpretation of the analysis of the reservoir rocks samples and make it more confusing and leads to overvalue the clay content because of causing higher magnetic susceptibility readings at lower magnetic fields and as a result showing weak relationship with permeability and the other petrophysics parameters[6].

Low & High Field Magnetic Hysteresis Study on Diamagnetic & Paramagnetic Minerals

Because of the good correlation with permeability shown by the high magnetic field susceptibility measurements derived from hysteresis curves; another set of experiments have been conducted using such measurements with magnetic field ranges up to 1000 mT and the results of these are summarized in Table 3 below: As shown in Figures 6 Quartz as a diamagnetic mineral shows straight line with negative slope at high magnetic field and as more percentage of Illite as paramagnetic is added the curve moves towards the positive direction with the curve of sample with the (96% Quartz & 4% Illite) lays exactly on the X-axis and the slope of the curve of the sample with 100% Illite is positive. The advantages of such curves that they give better idea about what is contained in the sample in question because they take advantage of the wide ranges of the applied magnetic fields and they can identify different components of the sample.

Magnetic Hysteresis Curves of Various Clays Found in Reservoir Rock Samples

Because of the important role the paramagnetic clays minerals play in controlling permeability in reservoir rocks; as increasing in one of these (e. g. Illite) of a few percent may cause permeability to be reduced by several times of amount, another set of experiments has been conducted by applying low magnetic field on samples contain mainly quartz and different clays percentages at the room temperature as shown in Table 4 and plotted in Figure 7.originally clays themselves highly differ in their magnetic susceptibility which is reflected on low field magnetic susceptibility measurements on the samples containing the same percentage of these clays and Quartz.

Low & High Field Magnetic Hysteresis Study on Diamagnetic & Paramagnetic Minerals plus Ferrimagnetic Minerals

Another set of experiments has been carried out at room temperature taking magnetic susceptibility measurements at low and high fields in order to investigate the effect of presence of ferri- ferromagnetic materials in reservoir rocks. One of the samples contains mainly diamagnetic minerals with a small percentage of ferromagnetic material (sample 1) while the second one contains mainly paramagnetic with a small percentage of ferromagnetic material (sample 2). This can be seen in Figure 8 which demonstrates that sample 1, for instance, contains mostly of diamagnetic material (quartz) as it exhibits nearly straight line with a negative slope while the slight kink at the low applied field indicates the presence of very small amount of ferrimagnetic material. In the same time, sample 2 exhibits nearly straight line with a positive slope which indicates that sample consists of paramagnetic (Illite), also the kink at the low applied field suggests the presence of a small ferrimagnetic mineral. This analysis helps to distinguish between diamagnetic, paramagnetic and ferrimagnetic minerals in the samples. Since ferrimagnetic minerals saturate at relatively low applied field, so their effect on the overall magnetic susceptibility can be quantified by taking high magnetic susceptibility readings by evaluating the size of the obtained kink.

Conclusion

In this paper, a number of experiments have been conducted trying to identify the presence of various minerals and their relative concentrations in syntactic samples using Low and high field magnetic susceptibility measurements using the MS2 B and VFTB in the petrophysics laboratory at Heriot-Watt University. This section summaries its findings in the following points:

About the Low Field Magnetic Measurements

The analysis of the synthetic samples is repeatable and it can be used to be applied on the real world rocks as the experimental and theoretical are very close to each other provided that the samples have two mineral-mixtures. Using the low field (rapid & non-destructive) magnetic susceptibility measurements is cheap and reliable. Plotting of such measurements against the percentage of the minerals in the samples can give an idea about the different components in the sample. The presence of other minerals in the reservoir rocks like ferrimagnetic should be taken into account to avoid overestimating the paramagnetic content such as clays and make wrong interpretations. Low field magnetic measurements represent the sum of all the components in the sample including the Ferri-and Ferromagnetic minerals.

About The High Field Magnetic Measurements

The usefulness of the high magnetic field measurements can be demonstrated in the presence of ferrimagnetic minerals, i.e. if the measurements in Figure 12, for instance, were taken at low field only and because of the kink (presence of ferrimagnetic); the amount of the paramagnetic minerals would be overestimated.The high magnetic field measurements can provide more information about reservoir samples than the single low field reading magnetic susceptibility measurements as the former can recognize various components by applying a range of magnetic fields. The high magnetic field measurements enable better approximation of paramagnetic and diamagnetic content without the effect of Ferro- or Ferrimagnetic components that might affect the low filed measurements.

Future Studies

The development of a downhole magnetic susceptibility tool would be potentially useful to perform these laboratory based predications at in-situ downhole. Analysis of magnetic susceptibility at reservoir temperatures and pressure in order to simulate downhole conditions. The information obtained will be used as input towards the development of the downhole susceptibility tool. The analysis is important since the magnetic susceptibility of minerals and compounds changes with a change in temperature for example according to the Currie-Weiss law. The application of the magnetic techniques in other reservoir types including tight gas and carbonates would be useful. This can be very important in particular with carbonates in the North Sea where permeability is often controlled by the presence of clays in the samples. And since magnetic measurements are of very high resolution and rapid, their application in tight reservoir can be potentially useful to figure out heterogeneities and their impact on permeability from these high resolution magnetic susceptibility measurements.

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Table 1 - *Experimental Magnetic Susceptibility vs. Theoretical Magnetic Susceptibility Results.*

Sample	**Description**	**Empty Box Weight (gm)**	**Box+Sample Weight**	**Experimental MS (10^{-8} m^3 kg^{-1})**	**Theoretical MS (10^{-8} m^3 kg^{-1})**
1	**100% Quartz**	3.0304	13.0304	-0.6	-0.6
2	99% Q + 1% Illite	3.0964	13.0964	-0.3	-0.444
3	98% Q + 2% Illite	3.0509	13.0509	-0.2	-0.288
4	96% Q + 4% Illite	3.1672	13.1672	0.2	0.24
5	94% Q + 6% Illite	3.1445	13.1445	0.4	0.336
6	90% Q + 10% Illite	3.0342	13.0342	0.8	0.96

Table 2 - *The Magnetic Susceptibility of the Samples With 0.1% Magnetite Results.*

Sample	**Description**	**The Mixture MS (10^{-8} m^3 kg^{-1})**
1	98.9% Q + 1% Illite+0.1 Magnetite	39.5566
2	97.9% Q + 2% Illite+0.1 Magnetite	39.7126
3	95.9% Q + 4% Illite+0.1 Magnetite	40.0246
4	93.9% Q + 6% Illite+0.1 Magnetite	40.3366
5	89.9% Q + 10% Illite+0.1 Magnetite	40.9606

Table 3 - *The Hysteresis Loops Measurements Results Of Different Concentrations of Quartz & Illite.*

Sample Description	**100% Diamagnetic**	**99% Dia+1% Para**	**98% Dia+2% Para**	**96% Dia+4% Para**	**94% Dia+6% Para**	**90% Dia+10% Para**	**100% Paramagnetic**
Mass magnetisation (10^{-6} Am^{2}kg^{-1}							
Magnetic Field (mT)							
-1000	620	463.8	307.6	-4.8	-317.2	-942	-15000
-800	496	371.04	246.08	-3.84	-253.76	-753.6	-12000
-600	372	278.28	184.56	-2.88	-190.32	-565.2	-9000
-400	248	185.52	123.04	-1.92	-126.88	-376.8	-6000
-200	124	92.76	61.52	-0.96	-63.44	-188.4	-3000
200	-124	-92.76	-61.52	0.96	63.44	188.4	3000
400	-248	-185.52	-123.04	1.92	126.88	376.8	6000
600	-372	-278.28	-184.56	2.88	190.32	565.2	9000
800	-496	-371.04	-246.08	3.84	253.76	753.6	12000
1000	-620	-463.8	-307.6	4.8	317.2	942	15000

Table 4 - *The Magnetic Susceptibility Measurements Results of Different Clays Types.*

Sample	**Description**	**Illite**	**Chlorite CFC**	**Smectite**
1	0%	-0.62	-0.62	-0.62
2	0.10%	-0.61844	-0.56688	-0.61618
3	0.20%	-0.58876	-0.51376	-0.61236
4	0.40%	-0.55752	-0.40752	-0.60472
5	0.60%	-0.52628	-0.30128	-0.59708
6	0.80%	-0.49504	-0.19504	-0.58944
7	1%	-0.4638	-0.0888	-0.5818

8	2%	-0.3076	0.4424	-0.5436
9	3%	-0.1514	0.9736	-0.5054
10	4%	0.0048	1.5048	-0.4672
11	5%	0.161	2.036	-0.429
12	6%	0.3172	2.5672	-0.3908
13	7%	0.4734	3.0984	-0.3526
14	8%	0.6296	3.6296	-0.3144
15	9%	0.7858	4.1608	-0.2762
16	10%	0.942	4.692	-0.238
17	15%	1.723	7.348	-0.047
18	20%	2.504	10.004	0.144
19	40%	5.628	20.628	0.908
20	60%	8.752	31.252	1.672
21	80%	11.876	41.876	2.436
22	100%	15	52.5	3.2

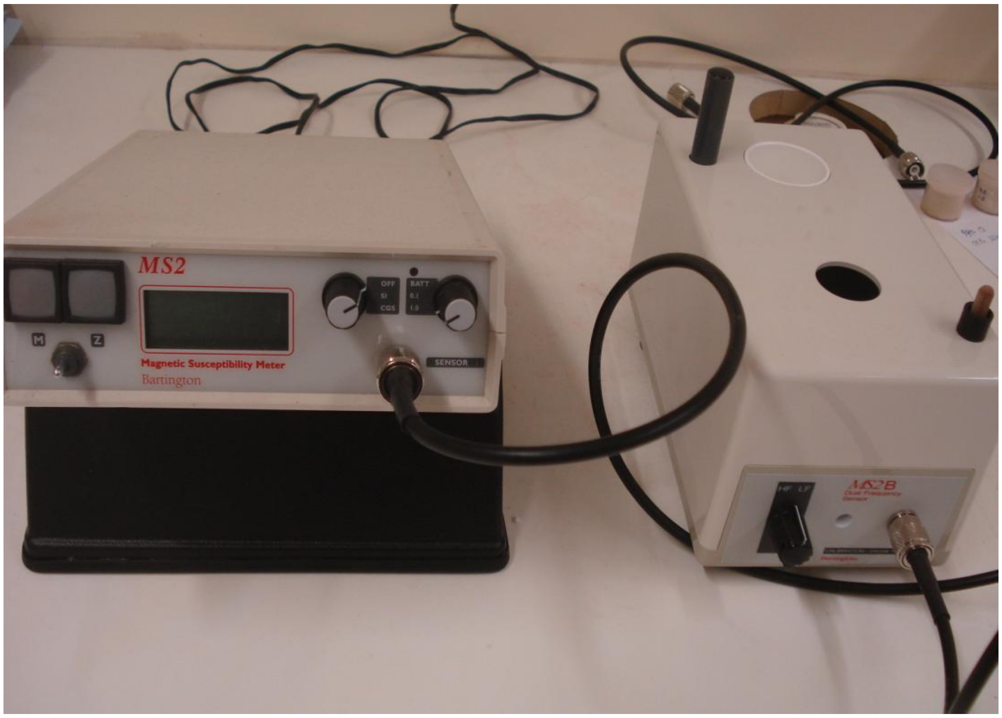

Fig. 1 – *Figure 4: MS2 B Dual Frequency Device.*

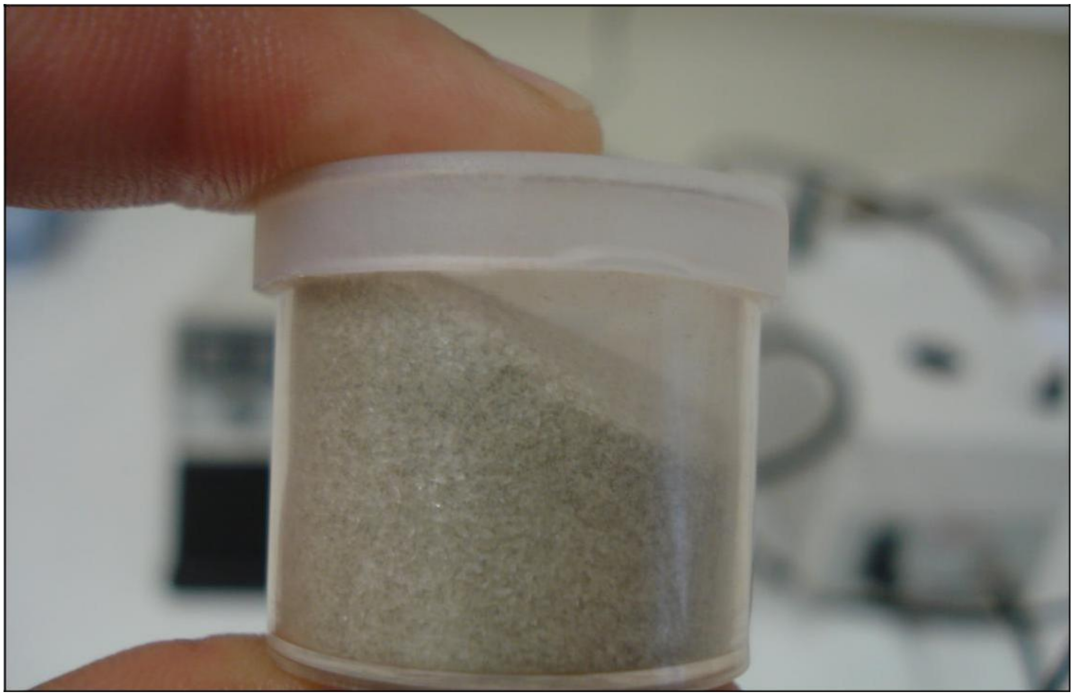

Fig. 2 – *A 20ml cylindrical bottle contains Quartz and Illite sample**.***

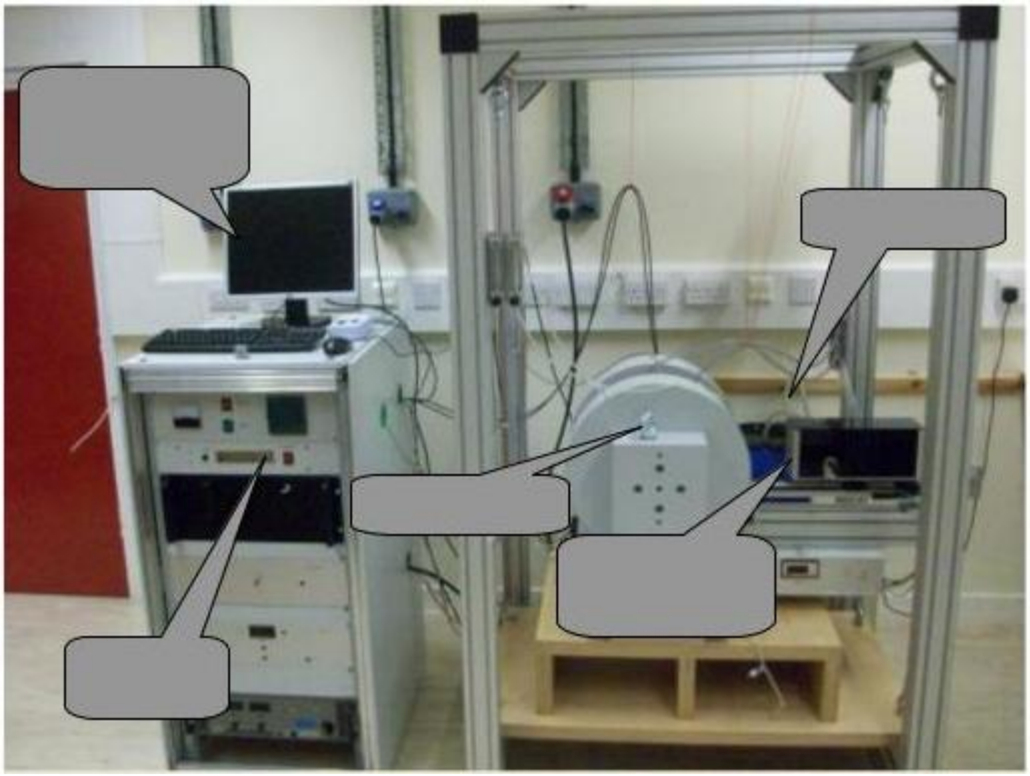

Fig. 3 – *Variable Field Translation Balance (VFTB).*

Monitoring of Measurements

Results

Water Tubing

Electromagnet
Automatic
Sample Holder
Electronic
Block

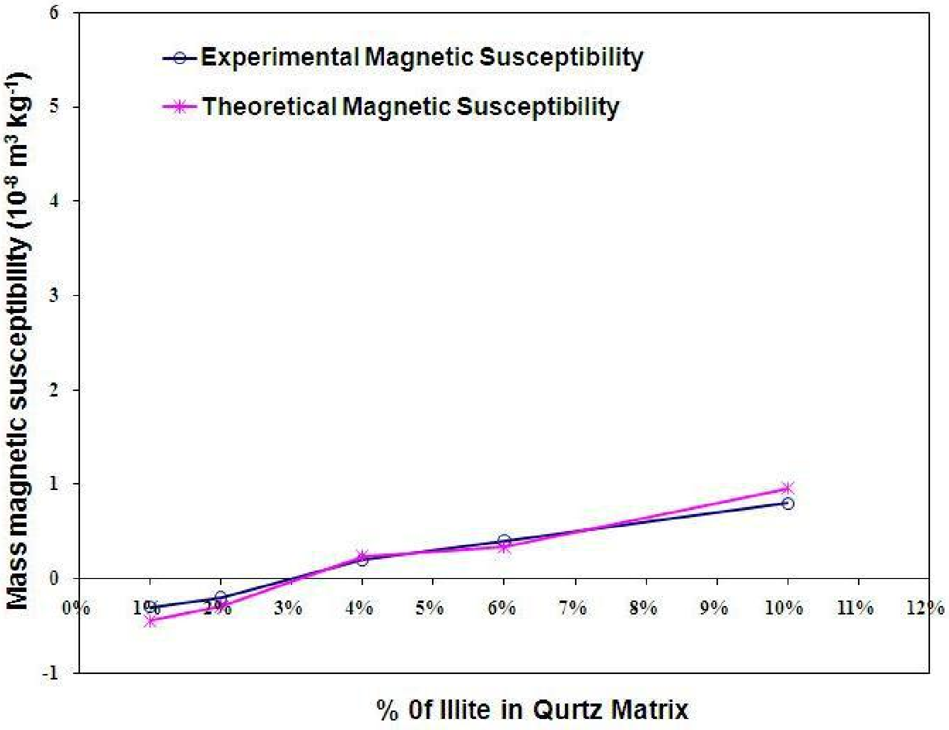

Fig. 4 – *Experimental Magnetic Susceptibility, Vs. Theoretical Magnetic Susceptibility.*

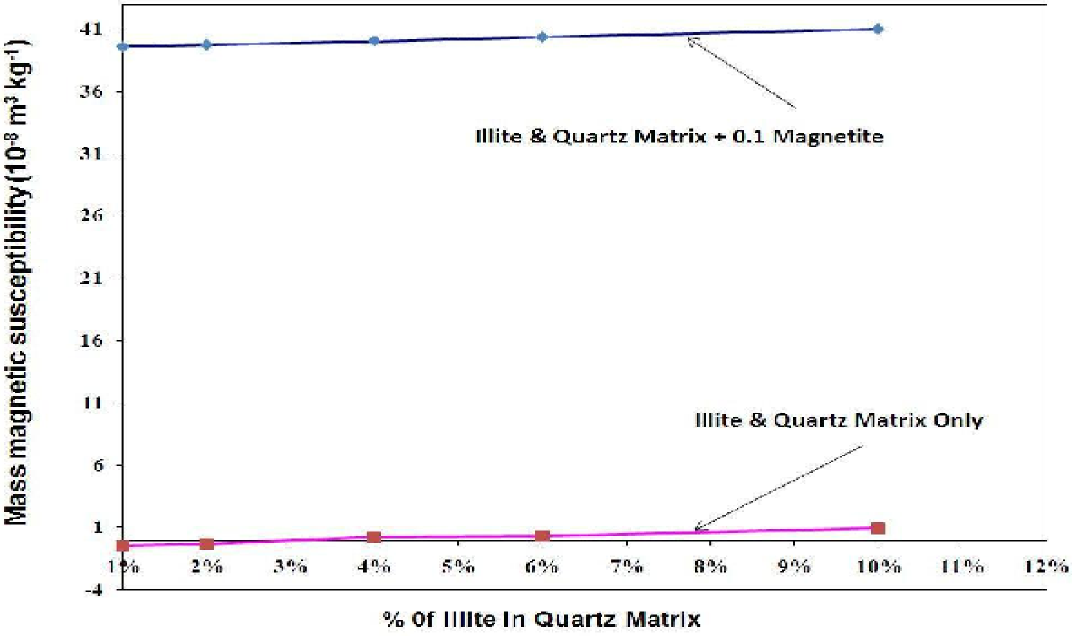

Fig. 5 – *The Magnetic Susceptibility Curves of the Sample with 0.1% Magnetite.*

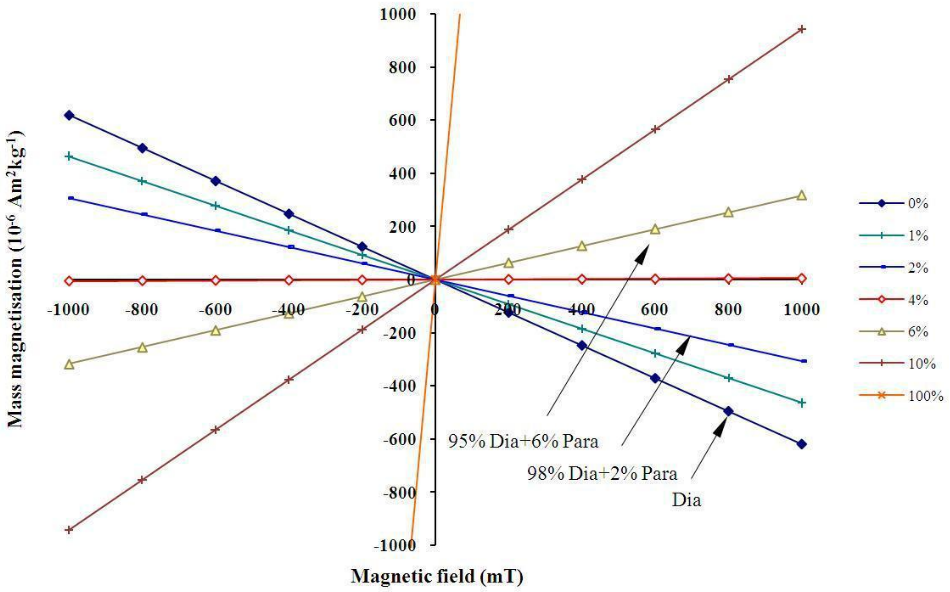

Fig. 6 –*The Hysteresis Curves Of Different Concentrations Of Quartz & Illite.*

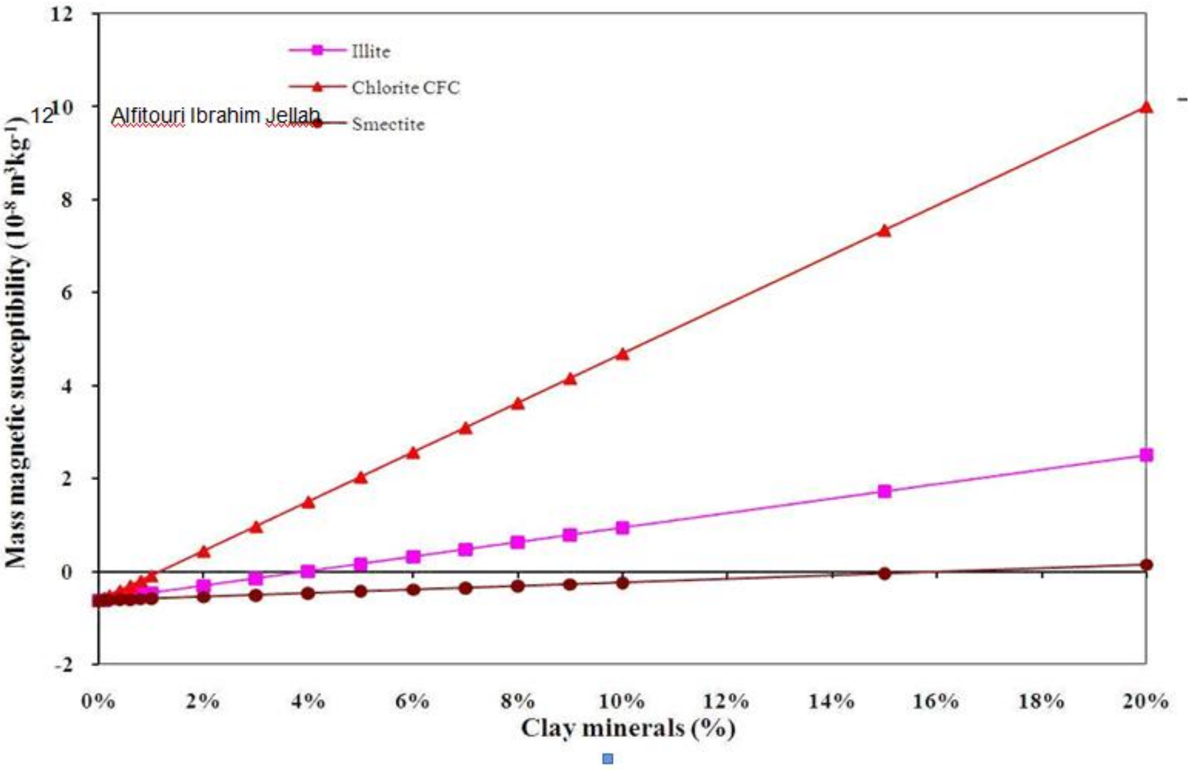

Fig. 7 – *The Magnetic Susceptibility Curves of Samples Contain Different Clays Types*

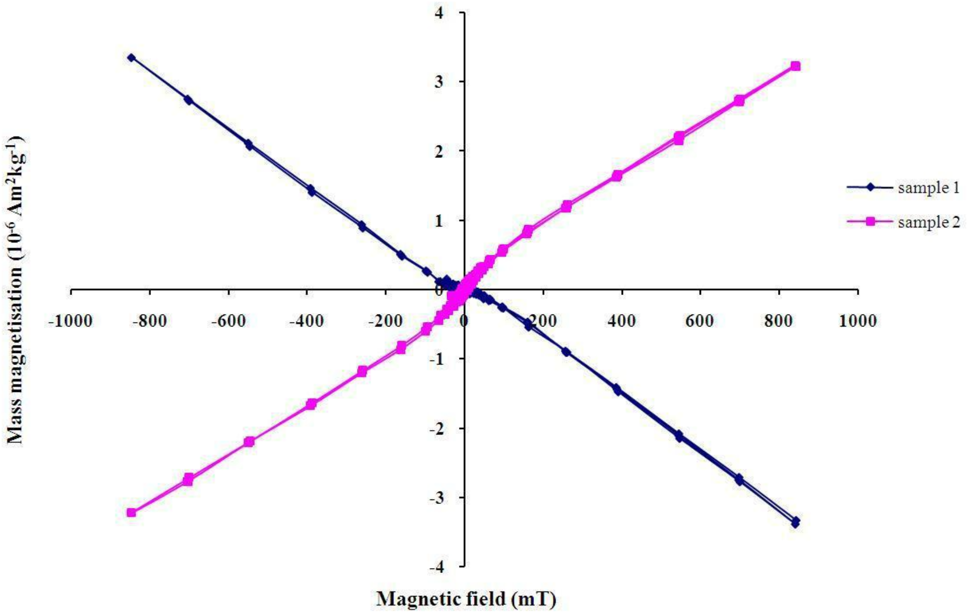

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Fig. 8 – *The Hysteresis Curves of Two Samples Containing Ferrimagnetic Impurities*