Journal of Environment and Earth Science
ISSN 2224-3216 (Paper) ISSN 2225-0948 (Online)
Vol. 3, No.11, 2013

Environmental Sustainability through Non-destructive Core Testing for Petroleum Reservoir Characterisation

Timothy Yakubu Woma[1*] Inusa I. Ewa[1, 2] Amaitem J. Iseh[1, 3]
1. Department of Pure and Applied Physics, Federal University Wukari, PM.B.1020 Wukari, Taraba State, Nigeria
2. Physics Department, Nasarawa State University,P.M.B. 1022 Keffi, Nasarawa State, Nigeria
3. Physics Department, University of Uyo, P.M.B 1017 Uyo, Akwa Ibom State, Nigeria
* E-mail of the corresponding author: timothy.woma@gmail.com

Abstract
There is growth in environmental concern associated with increase in petroleum production as energy demand continues to increase. Reduction in each of the several inter-related activities of petroleum production will ultimately lead to environmental sustainability. Conventional core testing is expensive, has little regards for environmental concern and is not based on geological, statistical and petrophysical criteria. Probe permeability and magnetic susceptibility measurements correlates well with conventional core testing results, and are possible ways to reduce environmental impact petroleum reservoir characterization
Keywords: Environmental, Non-destructive, Petroleum, Characterisation Core-testing, Magnetic, Permeability.

1. Introduction

World population growth and increasing per capita income especially in developing countries such as China, India and Nigeria comes with growing energy need. Due to increase in energy use that comes with increase in income, energy consumption is expected to triple in this century (Mohanty,2012). Because of economic, environmental and technological limitations of renewable and radioactive energy sources, petroleum –oil and gas must meet most of the increasing energy demand (Woma and Fagbenro 2013).
However, the increase in exploration and exploitation of petroleum comes with increasing adverse environmental impact which has lead to agitations and the accompanying tougher environmental legislation. Since petroleum exploration and exploitation involves several complex inter-related activities, the reduction in environmental impact of the individual activities will culminate into total reduction in the environmental impact of petroleum production. Thus this paper is an analysis of some of the non-destructive core testing techniques applicable in petroleum reservoir characterisation with regards to environmental sustainability.

2. Conventional/Traditional Core Testing

Conventional core analysis involves the cutting of core plugs followed by proper handling, cleaning and testing in the laboratory. Both routine core analysis (RCAL) and special core analysis (SCAL) are carried out for ground-truthing down hole wire line log data and for obtaining data for input into dynamic simulation models. Standard industry practice is to sample over a large cored interval. In RCAL horizontal plugs 2.5cm (1inch) diameter and 3.8cm (1.5inch) long are cut at regular sample spacing of 1 foot (about 0.3m) while vertical plugs are taken at sample spacing of 3 foot (about 1m).SCAL plugs are commonly at 6 foot spacing and for many purposes 3.8cm (1.5inch) in diameter.

This approach has little regards for the environmental impact of core analysis neither is it based on geological criteria and may bias the sampling such that some lithologies may be over sampled while others might be under sampled. A short review of the geological, petrophysical and statistical issues involved have been carried out by Corbett et al (Corbott etal,2001a.: Corbott etal,2001b).

The American Petroleum Institute (API) "Recommended Practices for Core Analysis" makes very little reference to environmental sustainability and sampling. The technical procedure for core plugs, probe permeameter and whole cores-including handling and cleaning- is laid out for these industry standard measurements. But the only comments about sample volume are for vugs, cherts,interlaminated shale and sands and conglomerates which says –"it is necessary that sample size be sufficient to include all pebble sizes" (API,1998). The comment about environment says "environmental concerns should also be considered and budgeted for. This may mean using a more expensive drilling fluid system to meet environmental objectives, or providing additional drilling fluid handling equipment to ensure containment."

There is therefore no guidance to industry on how samples should be located or suggestions about best practices that reduce the negative environmental impact of core analysis. The traditional core analysis procedure generates waste which needs treatment and/or disposal into the environment.

In contrast, a new cost effective sampling strategy is emerging that is based on selecting a small representative genetic unit (RGU) from available wire line log data and drill cuttings. A detailed analysis of the

RGU is performed, and is used as the bases for predicting a range of petrophysical parameters through out the rest of the wells and adjacent wells in the same field (Corbett etal,2001a; Corbett ettal etal,2001b Potter etal 1999; Potter and Corbett, 2000)

3. Probe Permeability

Conventional Core analysis using core plug results gives incomplete information about the reservoir as such sampling might be biased and are not environmentally friendly as core plugs need to be cut, cleaned out with chemicals thereby generating waste to be disposed into the environment. There is need to have sufficient samples that can give information about the reservoir at the lamina scale especially for heterogeneous reservoirs that are very difficult to manage. Corbett and Jensen introduced the concept of sample sufficiency and developed rules-of thumb that help in estimating the optimum number of samples that will be needed.(Corbett and Jensen,1992)

Probe Permeability allows one to obtain practically sufficient number of samples that represent a particular core interval. Probe permeability is measured using minipermeameter probes that provide high resolution, rapid, cheap and non destructive way of measuring permeability. The high resolution data from minipermeameter are at the lamina scale and can identify small scale heterogeneity such that key features are more likely to be identified.

Probe measurement data are less sensitive to missing core, improves depth matching to wire line log data and are environmentally friendly since no core plugs need to be cut nor waste generated to be disposed into the environment.

Minipermeameter estimate local absolute permeability by flowing gas through tubes sealed against the surface of core sample. Minipermeter are of two types: steady state minipermeameters and unsteady state (or pressure decay) minipermeameters.

Research in previous years have shown that in many cases core plug permeability and probe permeability measurements give very similar values(Potter and Corbett, 1999. Dines 2004). An example can be seen in ***figure 1*** where plug and resinated core probe permeability measurements from a North Sea oil well give essentially similar results. However in some North Sea examples the core plug permeabilities are higher than the probe permeabilities at comparable depths. The major reason for this variation is the fact that core plugs have been cleaned and dried whereas the slabbed core used for the probe measurements which is not cleaned has significant dried out hydrocarbons, which are causing a slight reduction in the measured probe permeability values (Woma,2008).

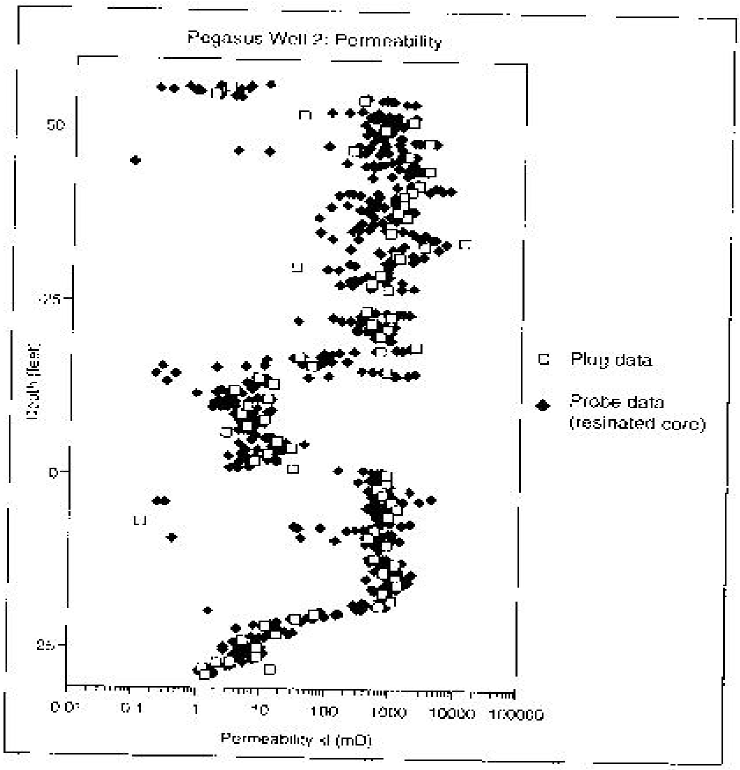

Figure 1. Plug and probe permeability measurements from a North Sea oil well give very similar result

4. Use of Magnetic Susceptibility Probe for Permeability Prediction

Magnetic susceptibility is the ratio of the intensity of magnetisation to the applied magnetic field strength. Mathematically the mass susceptibility is given as:

$$X = J/H \qquad (1)$$

Where J is the magnetisation per unit mass, and H is the magnetic field strength.

Generally materials are paramagnetic, diamagnetic or ferromagnetic (ferro - and ferrimagnetic). Materials with positive susceptibility (X) such that $(1+X) > 1$ are called paramagnetic materials. In the situation where susceptibility (X) is negative such that $(1+X) < 1$ the material is said to be diamagnetic. Ferromagnetic materials differ from paramagnetic and diamagnetic materials in that they have very high positive susceptibility such that they are able to retain their magnetic field.

The measurement of magnetic susceptibility is achieved by quantifying the change of force felt upon the application of a magnetic field to a substance. For liquid samples it is measured from the dependence of the natural magnetic resonance (NMR) frequency of the sample on its shape or orientation. Other methods have been successfully used to measure fluid susceptibility, for example, Sherwood Scientific Magnetic Balance (MSB) Mark I and Magnetic Properties measuring System (MPMS2) SQUID magnetometer (Ivakhnenko and Potter, 2004). The susceptibility values of common reservoir rock/ minerals and fluids as summarised by Potter et al (2004) and Hunt et al (1995) is given in table1.

The main factors controlling permeability in clean sandstone include: grain size, shape, sorting, packing, degree of consolidation, cements (quartz overgrowth, barite etc) and fractures. Additionally in muddy sandstone clay content (especially permeability controlling clays like illite or chloride) also control permeability while in shales the major factors controlling permeability are increased clay content (especially illite and chlorite), decreased quartz grain size and anisotropy (Tiab and Donaldson 2004). Mikkelsen et al (1991) and Vernik (2000) also affirm that permeability depends on the amount of clay minerals like illite, chlorite and kaolinite present in a sample. It has also been reported that the presence of illite can bridge pore space and create microporous rims that considerably reduces permeability with little effect on porosity (Potter etal, 2004; Cade etal.1994;Hurst and Nadeau,1994)

Considering the difference between the susceptibility of matrix minerals and permeability controlling clays, the sign of the raw magnetic susceptibility can be very useful for permeability and lithological zonations. Research in the past few years have continuously shown that excellent correlations exits between the net values of magnetic susceptibility and main permeability and lithological zones in a shallow marine shoreface Para-sequences (Potter 2004; Dines, 2004; Arge, 2007). figure 2 display the correlation; net susceptibility is generally negative in the high permeability clean sand units indicating the predominance of diamagnetic quartz and feldspar while in the low permeability muddy sand and shale units the net susceptibility has positive values indicating the higher percentage of paramagnetic illite clay and minor quantities of other paramagnetic and ferromagnetic minerals.

Processing the raw magnetic susceptibility into mineral content percentage provide even better correlation with key petrophysical properties. Potter et al. (2004) have developed a formula for calculating the mineral fraction assuming a two-component system. The total susceptibility from a sample is expresses as:

$$X_T = (F_I.X_I) + (1\text{-}F_I)X_Q \qquad (2)$$

Where X_T = Total measured susceptibility, X_Q = Known susceptibility of quartz (from table 1), X_I = Known susceptibility of illite and F_I is the fractional volume of illite which can also be expressed as:

$$F_I = (X_Q - X_T)/ (X_Q - X_I) \qquad (3)$$

The above equations are true for both volume susceptibility and mass susceptibility and illite content calculated using equation 3 from magnetic susceptibility measurements correlates with X-ray Diffraction derived illite content as shown in figure 3.

The calculation of mineral (illite) content can be extended to a whole range of other simple mineral mixtures for any given core material undergoing analysis, especially that magnetically derived illite content has been found to show very good correlations with horizontal plug permeability for a North Sea well as shown in figure 4 (Potter, 2004). Thus permeability in clean sand(corresponding to lower magnetically derived illite content) is expected to be higher than permeability in muddy sand (corresponding to higher magnetically derived illite content), however, this is not true for low permeability naturally barite- cemented regions (Potter, 2007). The naturally barite cemented regions are undetectable by the magnetic susceptibility technique because barite that is a paramagnetic mineral has susceptibility approximately the same as the susceptibility of diamagnetic quartz.

Since an excellent correlation exists between magnetically derived illite content and horizontal plug permeability gotten through conventional core analysis, the magnetic susceptibility measurements can be used to replace conventional core analysis methods. Magnetic susceptibility measurements are rapid, cheap,non-destructive and environmental-friendly as no plugs need to be cut and cleaned, therefore no waste will be generated or disposed into the environment. Thus the replacement of conventional core testing method with magnetic susceptibility measurements will be another step further in achieving environmental sustainability.

Table 1. Magnetic Susceptibility of Common Reservoir Minerals and Fluids.
(*After* Potter et al. 2004, and Hunt et al. 1995)

Type of mineral	**Mineral**	**Susceptibility per unit mass ($10^{-8}m^3$/Kg)**	**Susceptibility per unit volume (10^{-6} SI)**
Diamagnetic minerals	Quartz	-0.55	-13 to -17
	Calcite	-0.3 to -1.4	-7.5 to -39
	Orthoclasse Feldspar	-0.49 to -0.67	
	Kaolinite	-2.0	-50
Paramagnetic minerals	Illite	15.0	410
	BVS Chlorite	13.6	
	CFS Chlorite	52.5	
	Pyrite	2.0	35 to 5,000
Ferrimagnetic minerals	Magnetite	20,000 to 110,000	1,000.000 to 5,700,000

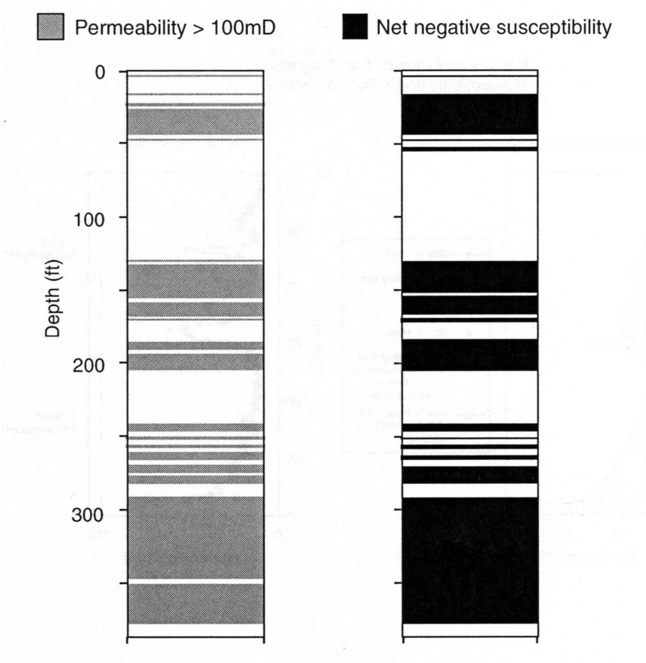

Figure 2. Correlation between Net Susceptibility Values and Main Permeability and Lithological Zones in a N. Sea Oil Well (From Potter, 2004).

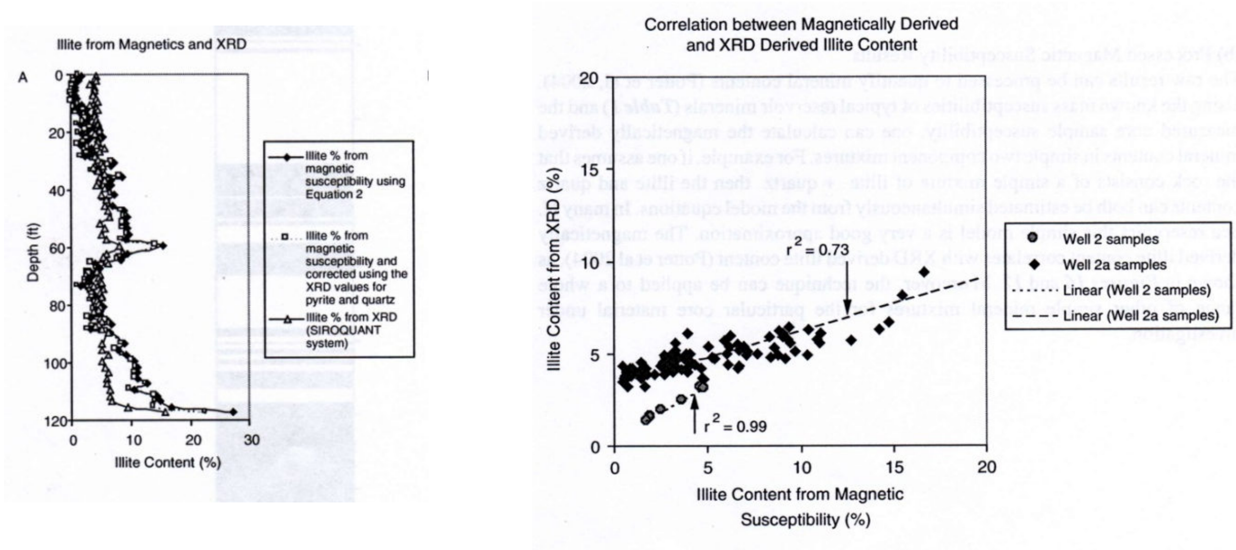

Figure 3. Good Correlation between Magnetically Derived Illite Content and XRD Derived Illite Content (From Potter et al, 2004).

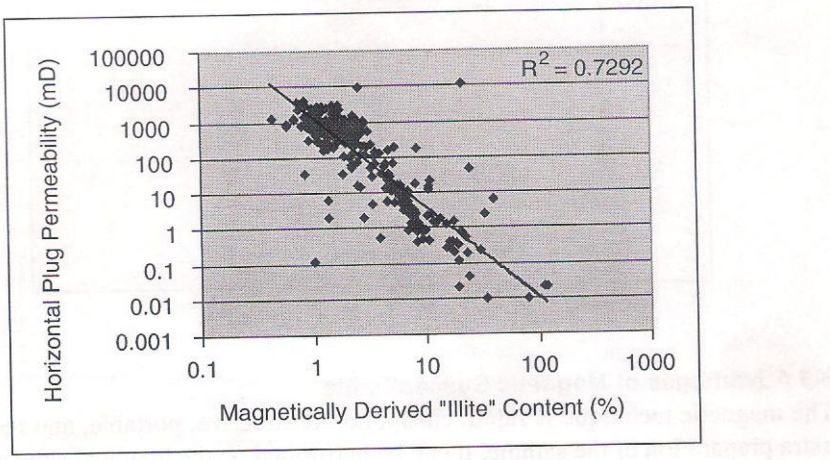

Figure 4. Magnetically derived illite content versus horizontal plug permeability in a North Sea oil well (From Potter, 2004)

5. Conclusion

Conventional/traditional Routine and Special core analysis methods of core testing generates waste which are disposed into the environment in addition to other geological, petrophysical and geostatistical issues involved. Probe permeability and magnetic susceptibility techniques of core measurement have been found to be environmental friendly, cheap, rapid, non-destructive and good alternative methods for core analysis applicable in reservoir characterisation. The replacement of conventional core analysis methods with probe permeability and magnetic susceptibility measurement techniques will reduce the amount of oil and gas industry generated waste disposed into the environment and can be a step further in achieving environmental sustainability.

.

References

API, (1998). Recommended Practices for Core Analysis. American Petroleum Institute, Washington

Arge, H. W., (2007), "The Relationship between Magnetically Derived Illite Content and Permeability in a Clastic Reservoir" MSc Petroleum Engineering Project Report 2006/2007, Heriot –Watt University, Edinburgh. *Unpublished.*

Cade, C.A., Evans, I.J. and Bryant, S.L., (1994), Analysis of Permeability Controls-a new approach: Clay Minerals, vol.29, no.4, pp.491-501.

Corbett, P.W.M., Jensen,J.L.,(1992). Estimating the mean permeability: How many measurements do you need? First Break,10, pp.89-94.

Corbett, P.W.M., Potter, D.K., and Bowen, D.G.,(2001). A new petrophysical sampling strategy for a model-dominated user group using an experimental design checklist approach. Proceedings of the 2001 International Symposium of the Society of Core Analyst, paper SCA 2001-01

Corbett, P.W.M., Potter, D.K., Mohammed, K., and Liu, S., (2001). Forget better Statistics- concentrate on better sample selection. DiaLog, 9, issue 2 June 2001

Dines, A. V., (2004), "Novel Magnetic Measurements, for Petrophysical Parameter Prediction" MSc Reservoir Evaluation and Management, Project Report 2003/2004, Heriot –Watt University Edinburgh. *unpublished*.

Hunt, C. P., Moskowitz, B.M., Banerjee, S.K., (1995), "Magnetic Properties of Rocks and Minerals" in Athens T.J. (ed) Rock Physics and Phase Relations: a Handbook of Physical Constants, pp.189-204, American Geophysical Union, Washington, USA.

Hurst, A. and Nadeau, P., (1994), A Little Clay –Volumes of Problems, paper A in Transactions of the 16th European Formation Evaluation Symposium, pp. 1-21.

Ivakhnenko, O.P. and Potter, D.K., (2004),"Magnetic Susceptibility of Petroleum Reservoir Fluids". Physics and Chemistry of the Earth 29 2004, pp. 899-907.

Mikkelsen, M., Scheie, H., Rong, O. and De Boer, E.T., (1991), "Abnormal Permeability Behaviour of a NORTH Sea Sandstone Reservoir " *SPE Annual Technical Conference and Exhibition,* 6-9 Oct. 1991, Dallas, Texas.

Mohanty, K.K., (2012). Meeting tomorrow's energy needs, minimizing environmental impact. The Way Ahead, 8, issue1 pp14-15

Potter, D.K., 2004, "Magnetic susceptibility as a rapid petrophysical tool for permeability prediction". European Association of Geoscientists and Engineers 66th Conference, Extended Abstracts, Volume1, paper D018, EAGE meeting, Paris, June 7-10.

Potter, D.K., (2007), "Magnetic Susceptibility as a Rapid, Non-destructive Technique for Improved Petrophysical Parameter Prediction" *Petrophysics*, Vol. 48, No.3, June 2007. Pp.191-201

Potter, D.K., and Corbett, P.W.M., (1999)."Integration, Scaling and Cross-Correlation of Petrophysical Measurements" in PEGASUS A Managed Programme in Petrophysics,6th Progress Report, Heriot-Watt University Edinburgh, June 1999.pp.1.13-1.24.

Potter, D.K., and Corbett, P.W.M., (2000).Genetic petrophysics and data integration in PEGASUS- improved prediction of key parameters.European Association of Geoscientist and Engineers 62nd Conference, Extended Abstracts, Volume 1 paper X-12, EAGE meeting, Glasgow, May 29 – June 2.

Potter, D.K., Corbett, P.W.M., Barclay, S.A., and Haszeldine, R.S., (2004), Quantification of illite content in sedimentary rocks using magnetic susceptibility rapid complement or alternative to X-ray diffraction. J.Sed.Res., Research Methods Papers Section, 74, no. 5, pp730-735.

Potter, D.K., Wright, J.M., and Corbett, P.W.M., (1999). A genetic petrophysics approach to facies and permeability prediction in a PEGASUS well. European Association of Geoscientist and Engineers 61st Conference, Extended Abstracts, Volume 1 paper 2-53, EAGE meeting,Helsinki, June 8-11.

Tiab, D. and Donaldson, E. C., (2004), "Petrophysics: Theory and Practice of Measuring Reservoir Fluid Transport Properties", 2nd edition, Elsevier, Inc. USA, pp.100-124.

Vernik, L., (2000), "Permeability Prediction in Poorly Consolidated Siliciclastics Based on Porosity and Clay Volume Logs" *Petrophysics*, Vol.41,No.2, 2000.

Woma, T.Y. (2008), "Comparison of three new portable probes(magnetics and miniperm)" MSc Reservoir Evaluation and Management, Project Report 2007/2008, Heriot –Watt Universiyt Edinburgh. *Unpublished*

Woma, T.Y. and Fagbenro, A.W., (2013), "Application of Time Lapse (4D) Seismic for Petroleum Reservoir Monitoring and Management.-A review," *Advances in Physics Theories and Application,* Vol.23, September 2013, pp.5-10.