Determination of Electrical Parameters in Carbonates with Micro-CT, NMR and Gas Displacement Experiments

Wang Kewen[1], Li Ning[1,2], Wu Hongliang[1], Zhang Gong[2], Feng Zhou[1],Yu jun[1]

[1] Research Institute of Petroleum Exploration & Development, PetroChina, Beijing 100083, China;
[2] Yangtze University, Jingzhou, 434023;

This paper was prepared for presentation at the International Symposium of the Society of Core Analysts held in Trondheim, Norway, 27-30 August 2018

ABSTRACT

Understanding the electrical characteristics of carbonate formation and accurately determining the electrical parameters (cementation exponent m and saturation exponent n in Archie equation) are very important for carbonate formations evaluation. However, the study of electrical characteristics faces great challenge because of the variable pore types, the complicated pore structure and the big heterogeneity in carbonates. We selected representative carbonate cores to carry out experiment research based on newly developed technologies in digital core analysis and resistivity test. Three types of cores were selected: the void space is mainly intergranular and intercrystalline; the vugs are developed; the fractures are developed. Firstly, the porosity and permeability of the selected cores have been tested. Then micro-CT with high resolution is used to scan the cores and NMR T2 spectrums of the cores both in water-saturated state and in bound water state are obtained. Finally, the resistivity of the cores in different water saturation is tested by using gas displacement technology. The analysis results of the experimental data show that the intergranular and intercrystalline pore and the fracture both have great influence on R_0 while the influence of secondary vug on R_0 is slight. Cementation exponent m and saturation exponent n have great difference between different cores and there is no obvious relation between m, n and reservoir parameters (φ or K). However, if we classify the cores based on the pore type, and the values of both m and n have good relationship with bound water saturation.

INTRODUCTION

Carbonate formation is an important oil–gas exploration field around the world. It is very important to understand the electrical characteristics of carbonate formation and accurately determine the electrical parameters for carbonate formations evaluation. However, the study faces great challenge because of the variable pore type, the complicated pore structure and the big heterogeneity in carbonates [1].

Archie formula indicated the relationship between petrophysical parameters (for example φ, Sw) and electrical properties in reservoir rocks [2]:

$$F = \frac{a}{\varphi^m} \quad \text{and} \quad I = \frac{b}{S_w^n}$$

Where F is formation factor, φ is porosity, m is cementation exponent, I is the resistivity index, S_w is the water saturation and n is the saturation exponent. The a and b are two constants. In general, the researches of the carbonate electrical properties can be classified into two kinds: The one is based on extensional conduction modes including the contributions of different pore types [3-5]. The conduction modes in this type are relatively complex, and contain more undetermined parameters. The other is mainly focused on non-Archie behaviour based on Archie formula. In this type, the Archie formula is used to describe the electrical behaviour. The main parameters m and n are not constant, and depend on the properties of the carbonate formation, such as wettability, pore structure and so on. In this paper, we select the later method. At first, we use Micro-CT and NMR to study the pore structure of the carbonate cores. Then the resistivity of the cores in different water saturation is tested by using the gas displacement technology. Finally, we analyze the influence of different pores on carbonate resistivity, and discuss the method of determination m and n.

SAMPLE SELECTION

All of the cores used in the experiments are from the Ordovician carbonate formation of Ordos Basin in China. They can be divided into three types: In the type I, the void space is mainly intergranular and intercrystalline, and the secondary vug and fracture are not developed; in the type II, the cores contain developed vugs besides intergranular and intercrystalline pores; in the type III, fractures are developed. These cores represent the typical pore types in carbonate formation. The diameter of all cores is the same value (2.5 cm). The porosity is between 2.2% and 15.1%, and the permeability is between 0.01mD and 17.01mD. The main petrophysical parameters of the six cores which belongs to different type mentioned above, have been given in Table 1.

CT AND NMR EXPERIMENTS

Micro-CT is an important technology for 3D pore structure analysis, which has been widely used in core analysis and reservoir evaluation in recent years. The resolution of the Micro-CT depends on the performance of the CT device and the size of the tested sample: the bigger size of the sample has the lower resolution, and the smaller size of the sample has the higher resolution. For the research of carbonate pore structure, there is a contradiction in single CT. On the one hand, we hope to observe the type of the secondary pores and their distribution in the samples. It requires the size of the tested sample is as big as possible and so the CT resolution cannot be high. On the other hand, we hope to observe the primary pores (such as intergranular and intercrystalline pores) and their connectivity in the core, which requires that the CT resolution is as high as possible, and the size of the tested sample must be small. Therefore, we cannot meet the above two objects at the same time if only single CT experiment is conducted.

Relaxation signal of NMR includes the information of water in the pores with different pore sizes. Based on the inversion of the echo, we can gain T2 distribution which can be used to analyse pore structure: The longer T2 relaxation time corresponds to the bigger pore size and the shorter T2 relaxation time corresponds to the smaller size. The T2 spectrum of the water-saturated core includes the information of all the pores while the centrifuge T2 spectrum only represents the bound water in micro-pores.

In this paper, the Micro-CT (nanotom) and NMR (MARAN-DRX/2, 2MHz) are used together to describe the pore structure of the carbonate cores. With Micro-CT, the type of the secondary pores and their distribution can be observed. The primary pores and their connectivity in the core can be analysed with NMR T2 spectrum. The resolution of the Micro-CT is 10um in our experiments. In other words, we cannot observe the pores whose size is smaller than 10um. Fig.1 gives the Micro-CT images of the six typical carbonate cores. Fig.1(a) and Fig.1(b) correspond to the samples in group I, Fig.1(c) and Fig.1(d) correspond to the samples in group II, and Fig.1(e) and Fig.1(f) correspond to the samples in group III. Fig. 2 gives the NMR test results of the six typical carbonate cores. Fig.2(a) and Fig.2(b) show the T2 spectrum in the group I, Fig.2(c) and Fig.2(d) show the T2 spectrum in the group II, and Fig.2(e) and Fig.2(f) show the T2 spectrum in the group III. Both water-saturated T2 spectrums and centrifuge T2 spectrums have been shown in Fig.2 except Fig.1(e) (sample 121).

ELECTRICAL RESISTIVITY EXPERIMENT

After Micro-CT and NMR test, we conducted the electrical resistivity experiment by using the gas displacement technology [10]. In electrical experiments, two-electrode method has been used, the confining pressure is 3000psi and the temperature is room temperature. There are two reasons that we use gas in the drainage. One is that the samples are from the gas formation in Ordovician carbonate and the fluids in gas displacement are similar with real reservoir. The other is that the samples are tight and the gas can enhance the displacement efficiency.

DISCUSSION

Effects of Different Type of Pores on Carbonate Resistivity

Pore structure and fluid are two key factors that influences carbonate electrical properties. When there are two or more types of fluids in the pores, the effects of both fluid and pore structure are interweaved, and we will face greater difficulty in analysis the effect of pore structure on carbonate resistivity. However, when the core is water-saturated, the influence of the pore structure on resistivity is the most remarkable. Therefore, in the following, we will discuss the effect of different pores on resistivity under the water-saturated state.

In Table.1, the main experiment results of the six samples have been shown. We use F (while R0) to discuss the influence of the pore structure on resistivity, which can avoid the influence of the R_w in different experiments. In Table.1, the porosity of the sample 36 is similar with the sample 46, while the formation factor of the sample 36 is about twice of the sample 46. From both CT images (Fig.1) and T2 spectrums (Fig.2), we can find that the secondary pore in sample 46 is very little, while the secondary pore in sample 36 is very developed. If the porosity is the same, the number of pores in the core with small pore size is larger than that in the core with big pore size. The large numbers of pores with small size, which are mainly primary pores and distribute relatively uniformly in the core, can offer more electrical path based on percolation theory [11], and can greatly reduce the resistivity. Although the contribution of the single micro-pore to electrical conduction is little, the large numbers of micro-pores have great effect on electrical conduction. We can find that the sample 23 has no secondary big pores (vugs), and it has low F, too. Therefore, we can conclude that the isolated secondary vugs which are not connected by fracture, may have little contribution to the electrical conduction of the core although they have great effect on carbonate porosity. In other words, in the research of carbonate electrical properties, we cannot overlook the role of the micro pores.

From Table.1, we can find that the porosity of the sample 18 is higher than that of the samples 121 and 118, while the formation factor of the sample 18 is higher than that of the samples 121 and 118. We think that the low formation factor of the samples 121 and 118 samples can be attributed to the following two reasons: one is the effect of the fracture and the other is mico-pores. In CT images (Fig.1), we can observe the micro fractures both in samples 121 and 118, which can greatly reduce the resistivity. Moreover, by comparing the water-saturated T2 spectrums (Fig.2), we can find that both the samples 121 and 118 have more micro-pores than the sample 18. Based on the above analysis, the samples 121 and 118 may have more electrical conduction paths than that of the sample 18.

Based on the former discussion, we can find that different type of pore has different influence on carbonate electrical properties. In the three types of pores, the intergranular and intercrystalline pores and the fractures have great influence on F (or R_0), while the influence of secondary vugs is slight.

The Method of Determination m in Carbonate

Fig.3 shows the relationship between cementation index m and the porosity Φ, and Fig.4 shows the relationship between m and permeability K. In Fig.3 and Fig.4, we can find that the data points are very scattered although there is a certain correlativity between m and φ (or K). Because different pore has different influences on carbonate electrical properties, we cannot determine the value of the m only based on the porosity or permeability in carbonates.

Through experimental data analysis, we find that the cementation index m has good relationship with NMR bound water saturation Swi, as shown in Fig.5. The bound water saturation is obtained by centrifuge NMR data. In Fig.5, we can observe that the value of the m linearly reduce with the increment of the bound water saturation. The increasing of the bound water saturation means that the proportion of mico-pores in samples increases.

According to the above discussion, we can conclude that the increasing of the bound water saturation will lead to the reduction of both the resistivity of water-saturated core and the value of the m.

Moreover, from Table.1, we can find that the value of m in the carbonate samples with secondary vugs is usually larger than 2.0, while the value of m in the samples with micro-fracture is usually smaller than 2.0. For carbonate cores with secondary vugs, the vugs have little contribution to electrical flow and lead to relatively higher resistivity. On other hand, the vugs have great effect on the porosity, and the core with vugs usually has low bound water saturation once the water in vugs is drainaged. Therefore, the m value in the carbonate cores with secondary vugs is higher (>2.0).

For the carbonate samples with micro-fractures, micro-fractures have great contribution to the current and lead to low resistivity. On other hand, the samples with micro-fractures are usually tight, micro-pores are developed and the bound water saturation is high. Therefore, the m value in the carbonate cores with micro-fractures is low (< 2.0).

Based on the above discussion, the data of the cores with secondary vugs are at the top left in Fig.5, and the data of the cores with micro-fractures are at the low right in Fig.5. Fig.5 not only shows the change of the m, but also provides a new method to determine m: we can use NMR well logging data to dynamically determine m in the whole depth.

The Method of Determination n in Carbonate

The influence factors of the resistivity exponent n are more than that of the cementation index m. Therefore, the determination of n is more complex. The I-Sw curves of three typical cores are shown in Fig.6. In our experiment, the non-Archie behaviour of the I-Sw curve is not obvious (Fig.6). Therefore, we can use the Archie formula to describe the electrical relationship and determine the value of the n for each core. We examined the relationship between n and φ, and the relation between n and K. We find that these relationships are not obvious. Considering that the pore structure of the carbonate cores has great effect on electrical properties, we further divide the samples into two groups: in the first group, the value of m is larger than 2.0; in the other group, the value of m is less than 2.0. Even though we divide the samples into different groups, the data points in the relations between n and k are scattered as shown in Fig.7. The relation between n and φ has similar characteristics.

We examined the relation between resistivity exponent n and the bound water saturation Swi obtained by NMR, which is shown in Fig.8. We find that for the same group (m>2.0 or m < 2.0), the resistivity exponent n has good relation with bound water saturation Swi: for the samples with m value > 2.0, the resistivity exponent n increases with the increasing of the bound water saturation; for the samples with m value < 2.0, the resistivity exponent n reduces with the increasing of the bound water saturation. Based on this relationship, we can use the data of NMR well logging to determine n in carbonate formation, which is meaningful for the well logging evaluation.

CONCLUSION

Carbonate formation has different types of pores. Based on CT images and NMR T2 spectrums, we can examine and identify the type of the pores. Different types of pores have different influences on carbonate electrical properties. The micro-pores (intergranular and intercrystalline pores) and the fracture have great influence on R_0, while the influence of secondary vugs on R_0 is slight.

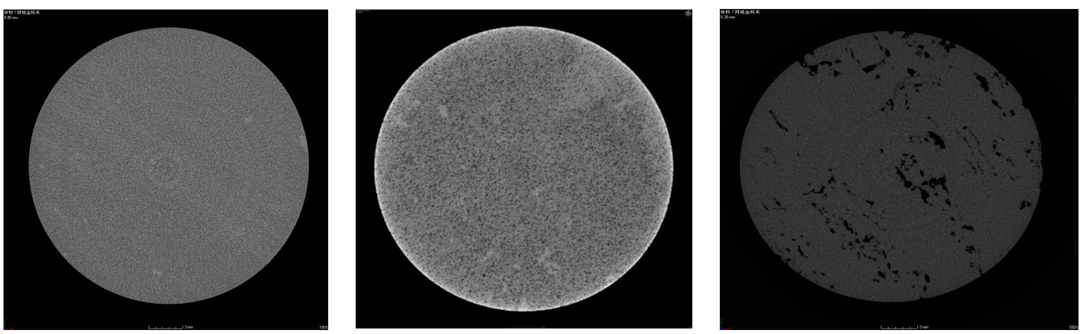
The value of m in the carbonate cores with secondary vugs is higher (normally larger than 2.0). The value of m in the carbonate cores with micro-fractures, are lower (normally lower than 2.0). Although the relationship between m and Φ (or K) is not obvious, the value of m linearly reduces with the increasing of the bound water saturation. If we classify the cores based on the pore type, the value of n in carbonates has better relation with bound water saturation than porosity and permeability.

REFERENCES

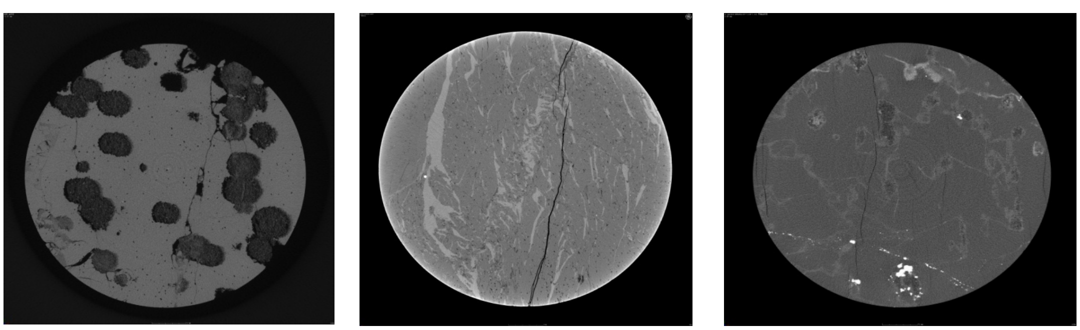
1. Klaas Verwer, Gregor P. Eberli, and Ralf J. Weger. Effect of pore structure on electrical resistivity in carbonates, AAPG Bulletin, 2001,95(2):175-190.
2. Archie, G.E.. The electrical resistivity log as an aid in determining some reservoir characteristics. J. Petroleum Technology, January, 1942.
3. Pabitra N. Sen, Resistivity of partially saturated carbonate rock with microporosity, Geophysics, 1997, 62(2):415:425.
4. Fleury M. Advances in resistivity measurements using the FRIM method at reservoir conditions: applications to carbonates. SCA International Symposium. SCA2003-31, Pau, France, September 21-24.
5. Aguilera M. S. and Aguilera R., Improved Models for Perophysical Analysis of Dual Porosity reservoirs, Petrophysics, Vol. 44. No.1, 2003
6. Talia Shamsi Ara , Soran Talabani, H.H.Vaziri and et al.. In-Depth Investigation of the Validity of the Archie Equation in Carbonate Rocks, SPE67204.
7. Ara T S, Talabani S, Vaziri H H et al. In-Depth Investigation of the Validity of the Archie Equation in Carbonate Rocks[C].2001, SPE67204.
8. M.R. Rezaee, H. Motiei, E. Kazemzadeh, A new method to acquire m exponent and tortuosity factor for microscopically heterogeneous carbonates, Journal of Petroleum Science and Engineering,2006
9. E. Muller-Huber and J. Schon, A modified Archies relationship- A novel approach to evaluate carbonate reservoir with regard to fracture and isolated vuggy porosity for sw=1, IPTC1669,2013.
10. Kewen Wang, Jun Yu, Qingfu Feng et al., Study of tight core electrical properties measurement by porous plate, SCA2014-069,2014.
11. Sahimi M. Applications of Percolation Theory [M]. Bristol: Taylor and Francis, PA, 1994.

Table 1 The main petrophysical parameters of six cores

Group	Core No.	Total Porosity (%)	CT Porosity (%)	unresolved CT Porosity (%)	Permeability (mD)	F	m	Swi
I	23	14.12	0	14.12	0.65	54.5	2.04	40
	46	15.27	2.64	12.63	17.01	46.7	2.05	30
II	18	6.29	5.02	1.27	1.75	627.5	2.33	11
	36	15.13	9.45	5.68	8.67	94.45	2.41	17
III	121	3.51	0.86	2.65	1.78	134.2	1.46	\
	118	5.05	0.35	4.7	0.164	193.5	1.76	86



a (No.23) b(No.46) c (No.18)



d (No.36) e(No.121) f (No.118)

Fig.1 The Micro-CT images of the six typical carbonate samples

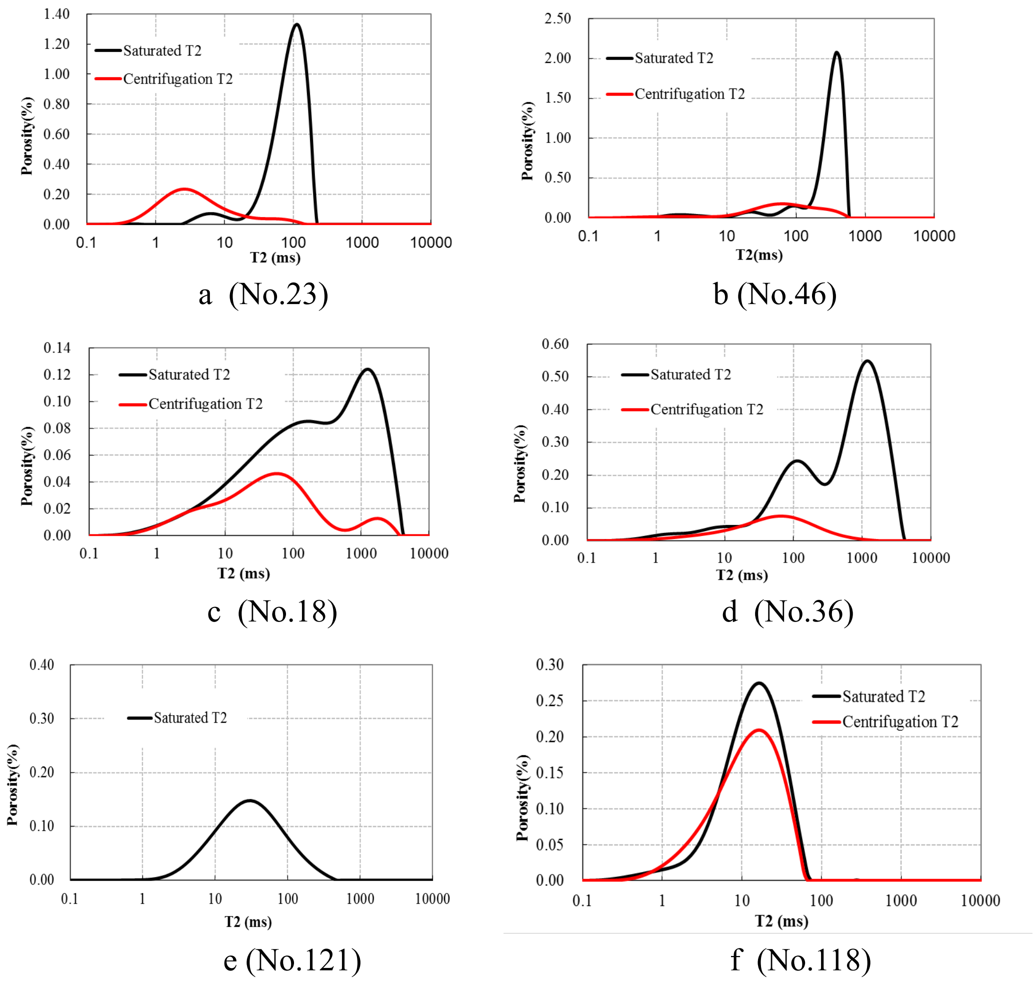


Fig. 2 The NMR test results of the six typical carbonate cores

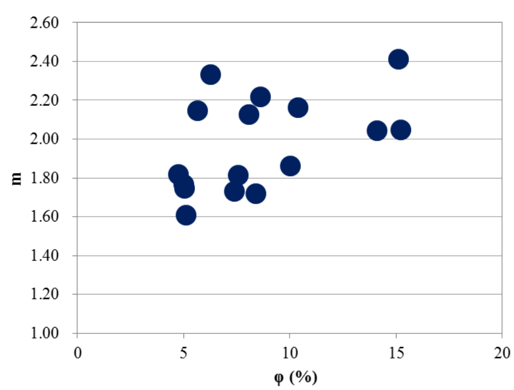


Fig. 3 The relationship between m and φ

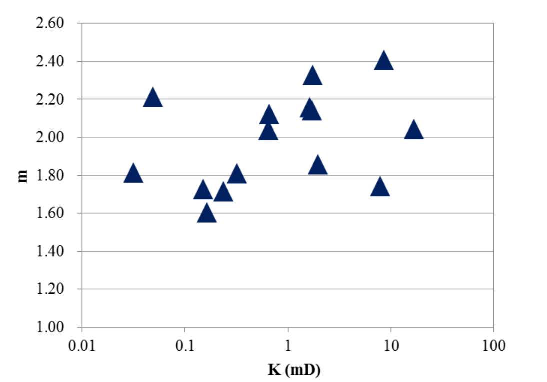


Fig. 4 The relationship between m and K

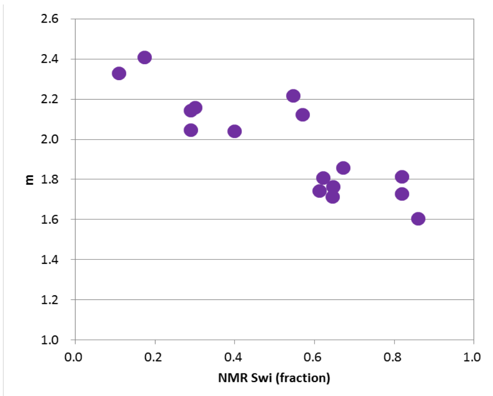


Fig. 5 The relationship between m and Swi

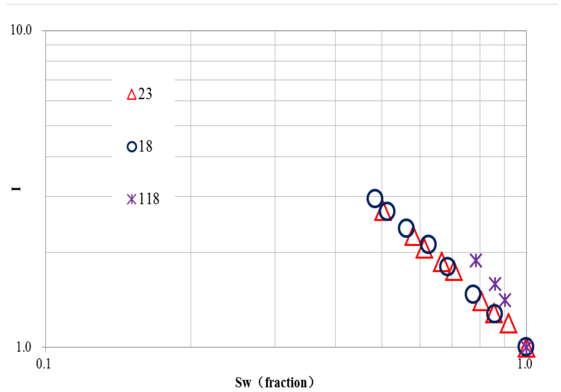


Fig. 6 The I-Sw curves of typical cores

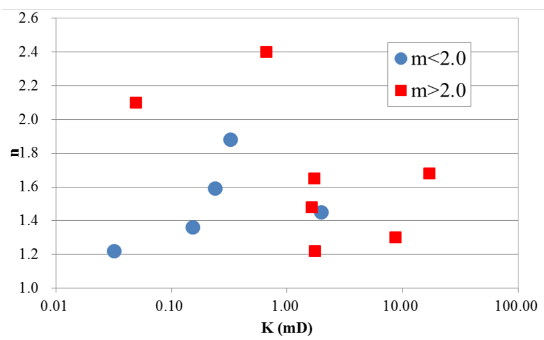


Fig. 7 The relations between n and k

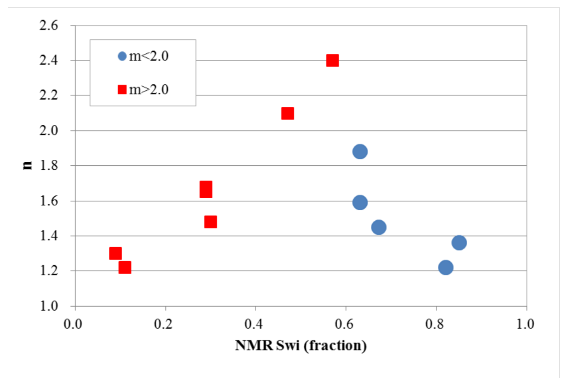


Fig. 8 The relation between n and Swi