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AN ALTERNATIVE METHOD TO EVALUATE AQUIFER PERMEABILITY

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New techniques are described to evaluate complex dual porosity aquifers using geophysical logs. Alternatives are presented to characterize highly heterogeneous rocks and identify the presence of primary and secondary porosity. Also, this methodology allows the evaluation qualitative indexes of permeability and petrophysical variables. Applications of these interpretive methodologies are presented for the karstic aquifer of the Northern Basin of Matanzas, Cuba.

INTRODUCTION

Aquifers can consist of intergranular voids combined with voids caused by fractures or solution features. Aquifers with these characteristics are referred to as having dual porosity.

The intergranular voids, created during the formation of the rocks, make up the primary porosity of an aquifer. Primary porosity can be continuous and homogeneous where petrophysical properties show small variation. Fracture or solution voids make up the secondary porosity of an aquifer. Aquifers with both primary and secondary porosity are referred to as having dual porosity.

Dual porosity aquifers show large variation in their petrophysical properties. Theoretical and experimental evidence exists that effective tools to characterize these aquifers are lacking. However, the task of characterizing these systems, and detecting the existence and nature of aquifer heterogeneities, is critical because it can give a more complete picture of the internal structure of geologic formations, and better define zones which can sustain a good water supply.

Water supply in Cuba consists of 74 percent groundwater. Groundwater occurs primarily in karstic calcareous rocks with dual porosity. It is clear that the study and protection of these aquifers is of highest importance, as is the development and application of more efficient investigation methods.

Over the last several years, there has been an increase in the number of geophysical works applied to the characterization of dual porosity karstic aquifers (Kobr, 1992). Geophysical logs can contribute valuable information during hydrogeological investigations, but the analysis and interpretation required to evaluate these aquifers represents a complex problem that has not been completely solved. The specialized literature reports a great variety of works on this topic. Mendoza and Valle (1996) refer the works of Aguilera (1976), Gómez-Rivero (1977, 1981), Raiga-Clemenceau (1977) and Rasmus (1983), who suggested the use of variables that appear in the general Archie equation as valuable tools for petrophysical characterization of geological formations. Of these, the empirical procedures developed by Gómez-Rivero are the most effective because they offer a detailed characterization of aquifer intervals under analysis.

Here we apply an alternative interpretation developed by Mendoza and Valle (1996), to characterize dual porosity aquifers.

CHARACTERISTICS OF THE STUDY AREA

The Northern Basin of Matanzas province, Cuba is developed in rocks of Neogene age that belong to the Güines Formation. The rocks include a great variety of limestones and a high degree of karstification. Thin lenses of clay also occur in the limestones. The high karstification of this formation has made it an excellent aquifer storing the largest groundwater resources in the province. Generally the aquifer is phreatic, except in low areas due to the presence of a thick clay overburden. To the east and west, the thickness of the aquifer is not greater than 30 m, in the central depression its thickness can reach up to 120 m.

The depth of the groundwater is between 2 and 8 m. Typical flows are from 100 to 200 l/s per m. The transmissivity coefficients vary from 5000 up to 100,000 m^2/d, the average is 11,000 m^2/d.

The direction of groundwater flow is from south to north, with little lateral inflow. The discharge is to the sea. The hydraulic gradients are low, between 10^{-2} and 10^{-4}. In general, saline intrusion does not exist. The content of chlorides is less than 100 mg/l and the total soluble salts are less than 1 g/l.

The study area is shown in Figure 1.

THEORY

Pérez-Rosales (1982) demonstrated that, from the point of view of electrical conduction, pore space is made up of regions which are conductive (channels) and regions which are not (traps). He established the following relationship:

$$\phi = \phi_f + \phi_s \quad (1)$$

where:

ϕ = total porosity,

ϕ_f = flow porosity, and

ϕ_s = trap porosity.

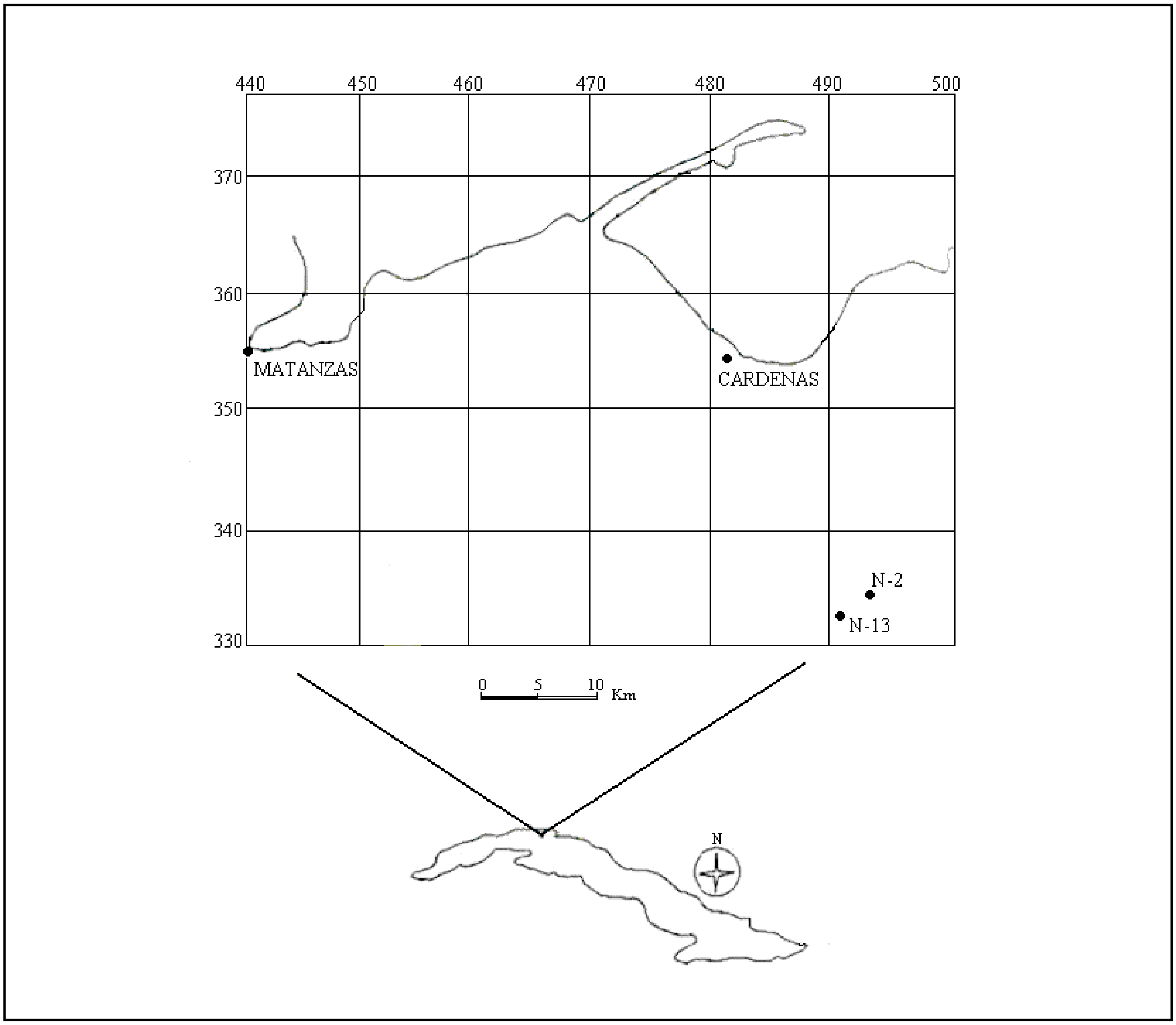

Figure 1. Wells locations studied in the Northern Basin of Matanzas, Cuba.

He further established that the flow porosity satisfies:

$$\phi_f = 1 \quad \text{when} \quad \phi = 1 \tag{2}$$

$$\phi_f = 0 \quad \text{when} \quad \phi = 0 \tag{3}$$

$$\phi_f \le \phi \quad \text{in the interval} \quad 0 \le \phi \le 1 \tag{4}$$

Condition (4) establishes that flow porosity cannot be greater than the total porosity, derived from (1). In this same study, Pérez-Rosales postulated that the simplest relationship that fulfilled the three previous conditions was:

$$\phi_f = \phi^m \quad m \ge 1 \tag{5}$$

Where m is a flow exponent, not a cementation coefficient as other researchers have proposed, which better describes the physical behavior and properties of rocks.

Pérez-Rosales (1982), using Maxwell's equation, developed compound systems as dielectric spheres suspended in a conductive medium, and demonstrated that it is possible to formulate the following general relationship known as the Pérez-Rosales equation:

$$F = 1 + G\left(\phi^{-m} - 1\right) \tag{6}$$

where:

m = flow exponent,

G = a parameter that depends on the porous internal geometry,

ϕ = total porosity, and

F = formation factor.

Average values of G determined by numerous laboratory measurements for carbonates and sand were 0.887 and 1.03, respectively. Starting from the expression (5) and (6) and measuring F from geophysical logs, it is possible to obtain the flow exponent and flow porosity.

To facilitate the practical application of this methodology, Abanico cross-plots were developed. These nomograms relate m and F for sands and carbonates. Mendoza and Valle (1996), explained the interpretation of this new nomogram and validated this methodology for locating petroleum and gas accumulations.

APPLICATIONS IN HYDROGEOLOGICAL INVESTIGATIONS

This interpretive method was applied to wells N2 and N13, located in the northern karstic aquifer at Matanzas, Cuba. These wells had already been interpreted applying the methodology developed by Gómez-Rivero (Valcarce, 1998).

Figure 2 shows the location of the parameters (F, ϕ) for each interval, obtained from electrical and the neutron logs respectively. From this graph it is possible to say that the points are located predominantly in the regions corresponding to:

- Communicating cavernous voids (denoted by the letters CC), where the total porosity presents high values (greater than 7 percent), and m takes smaller values (between 1 and 2), showing that the presence of traps is almost nonexistent. In this region, rocks with caverns and dissolution channels are well connected and of high permeability.

- Intergranular voids and high total porosity (denoted by IA), where the values of F are average to low, and m is average to high. In general, for this case m is smaller than 2.5, and in many cases

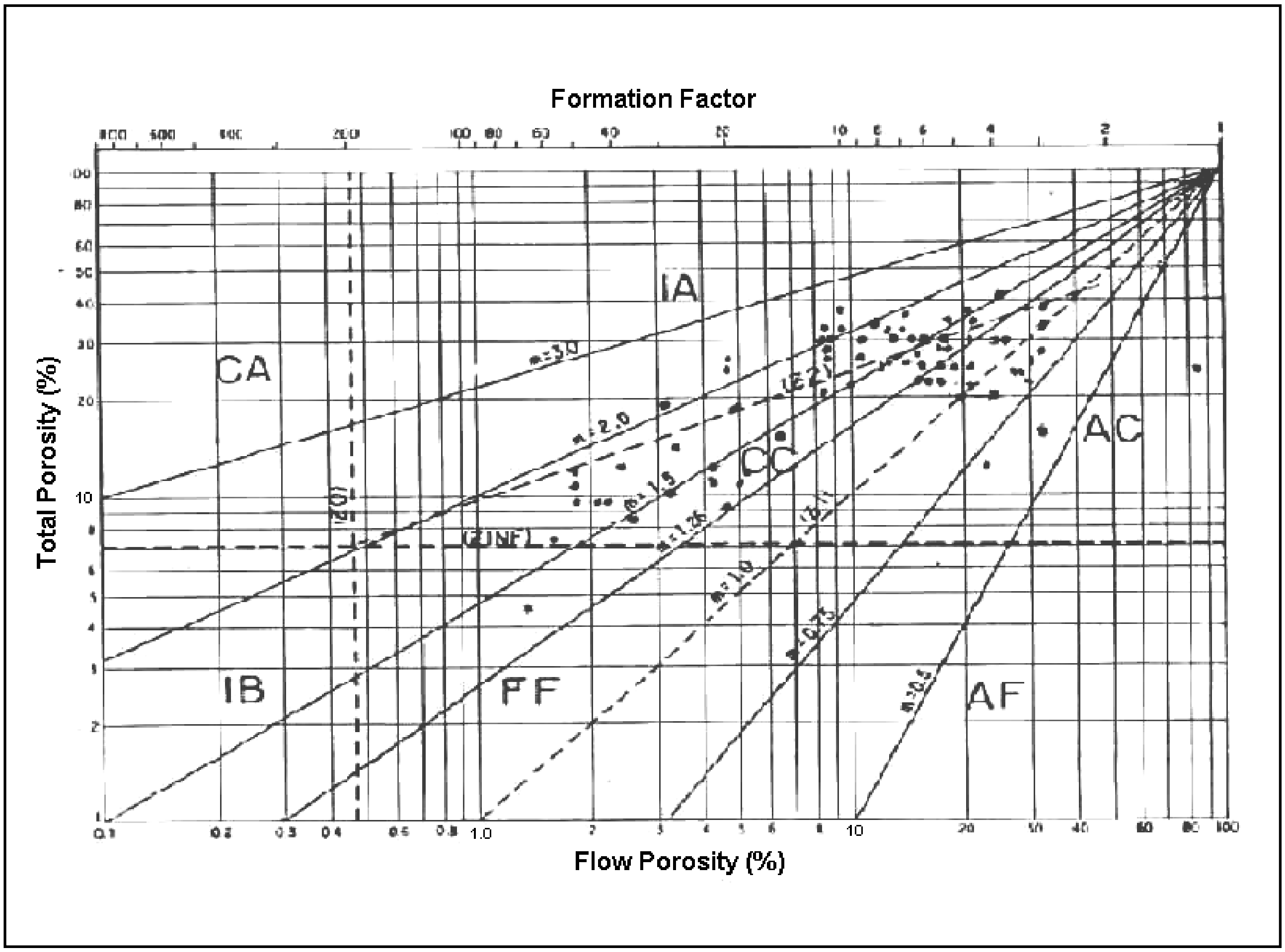

Figure 2. Abanico cross-plot to study carbonate rocks. (Mendoza and Valle, 1996).

smaller than 2. The total porosity is greater than 20 percent and it shows a low geometric complexity. There is little development of trapping areas, and permeability values range from average to high. This region, according to Mendoza and Valle (1996), is associated with sedimentary rocks of clastic texture with intergranular porosity. The well logs in this depth interval show karstic development. This void configuration we call neo-intergranular.

- Some intervals are classified as clayey cavernous (denoted by AC), with values of *m* less than 1 and flow porosity greater than the total porosity. This is inconsistent with the porosity concept and can be explained by the fact that this zone contains clays which have increased electrical conductivity, making flow porosity seem greater than the total porosity.

- An interval is located in the region of fractured voids (denoted by FF), where the total porosity and *m* have low values. These low values show that trap zones are almost non existent. This region corresponds to fractured rocks with very low intergranular porosity but high permeability because small fissures diminish trapping and increase the system flow capacity. This is reflected in the lowered values of *F* and *m*.

The results obtained applying this interpretation methodology coincide in general with those obtained using the cross-plots developed by Gómez-Rivero, as well as with the geologic descriptions of the wells (Valcarce, 1998). Tables 1 and 2 show these results in detail.

CONCLUSIONS

Table 1. Results Obtained in the N-2 Well

Depth	F	Φ_t (%)	m (G-R)	m (M-V)	Φ_f (%)	System type		Lithologic description.
						G-R	M-V	
11.0	3.1	17.8	0.66	0.60	35.0	CC	AC	
12.4	3.8	41.1	1.50	1.50	26.0	IA	IA	
13.4	4.1	19.8	0.87	0.85	25.0	CC	AC	
14.4	3.1	33.3	1.03	1.00	33.3	CC	CC	
17.6	3.8	12.4	0.64	0.70	23.2	CC	AC	
18.8	1.3	24.4	0.19	0.20	75.4	CC	AC	
22.4	5.9	22.0	1.17	1.20	16.2	CC	CC	
23.2	7.2	27.0	1.51	1.50	14.0	CC	CC	
24.0	6.3	24.4	1.30	1.30	16.0	CC	CC	
26.0	3.1	39.0	1.20	1.20	32.3	CC	CC	
28.6	3.1	27.1	0.87	0.85	33.3	CC	AC	
29.6	3.1	39.0	1.20	1.20	32.3	CC	CC	
31.6	3.4	24.4	0.87	0.85	30.0	CC	AC	
35.8	3.8	30.0	1.11	1.10	26.6	CC	CC	
40.0	3.1	22.0	0.75	0.80	29.7	CC	AC	
41.4	4.7	35.0	1.48	1.45	21.8	IA	IA	
43.0	5.0	25.7	1.18	1.20	19.5	CC	CC	
45.8	5.9	30.0	1.48	1.50	16.4	IA	IA	
46.6	4.7	37.0	1.56	1.55	21.4	IA	IA	
47.4	5.6	28.5	1.37	1.40	17.2	CC	CC	In the interval (3 and 60 meters) are described cavernous calcareous, porous, marls – loamy rocks.
48.4	4.7	33.3	1.41	1.40	21.4	IA	IA	
50.0	4.7	25.7	1.14	1.15	21.0	CC	CC	
51.2	5.6	30.0	1.43	1.40	18.50	CC	CC	
52.8	6.3	22.0	1.21	1.24	15.30	CC	CC	
54.6	8.8	30.0	1.81	1.80	11.40	IA	IA	
60.0	5.9	27.1	1.36	1.35	17.10	CC	CC	
61.4	5.3	22.0	1.10	1.10	19.00	CC	CC	
63.0	7.5	27.1	1.54	1.50	14.00	CC	CC	
64.6	68.0	4.4	1.30	1.30	1.72	FF	FF	
68.0	4.7	30.0	1.29	1.30	21.00	CC	CC	
71.6	22.0	12.4	1.48	1.40	5.40	CC	CC	
72.8	5.9	24.4	1.26	1.30	16.00	CC	CC	
74.2	16.5	16.1	1.53	1.50	7.20	CC	CC	In the interval (60 and 102 meters) are described calcareous cavernous and very cavernous rocks.
78.6	45.0	9.5	1.62	1.70	1.80	CC	CC	
82.0	21.0	13.0	1.50	1.50	4.60	CC	CC	
83.0	50.0	9.5	1.67	1.70	1.82	CC	CC	
84.8	22.0	11.2	1.41	1.40	4.66	CC	CC	
86.0	36.5	8.2	1.44	1.45	2.60	CC	CC	
87.6	27.0	16.1	1.80	1.80	3.70	CC	CC	
89.4	40.0	9.5	1.57	1.60	2.30	CC	CC	
91.6	36.5	13.0	1.77	1.80	2.50	CC	CC	
94.8	52.0	7.4	1.51	1.52	2.00	CC	CC	
96.0	19.0	12.4	1.41	1.40	5.40	CC	CC	
99.4	10.9	27.1	1.83	1.80	9.50	IA	IA	
101.4	28.0	10.1	1.45	1.48	3.30	CC	CC	

Table 2. Results obtained in the N-13 well

Depth	F	Φ_t (%)	m (G-R)	m (M-V)	Φ_f (%)	System type		Lithologic description.
						G-R	M-V	
19.8	19.0	19.3	1.77	1.80	5.0	IA	CC	In the whole interval they are described calcareous rocks with variable karstic development.
21.0	10.0	33.3	2.05	2.05	9.5	IA	IA	
22.4	50.0	11.5	1.79	1.80	1.9	CC	CC	
24.0	30.0	19.3	1.95	2.00	3.2	IA	IA	
26.0	50.0	11.8	1.81	1.80	1.8	CC	CC	
27.8	11.5	29.3	1.95	2.00	8.5	IA	IA	
28.8	9.2	20.9	1.40	1.50	9.5	CC	CC	
30.2	8.8	27.1	1.63	1.70	12.0	IA	IA	
31.4	11.0	30.0	1.96	2.00	9.0	IA	IA	
32.4	20.0	25.7	2.17	2.20	5.0	IA	IA	
36.0	8.0	34.2	1.89	2.00	11.7	IA	IA	
39.6	11.0	29.3	1.91	2.00	8.6	IA	IA	
41.2	10.0	32.5	2.00	2.10	9.4	IA	IA	
44.8	8.0	34.2	1.89	2.00	11.7	IA	IA	
47.4	6.7	33.3	1.70	1.80	13.8	IA	IA	
50.0	5.30	29.3	1.33	1.40	18.0	IA	CC	
51.8	4.7	21.4	0.99	1.00	21.4	CC	CC	
54.8	10.0	38.0	1.73	2.50	9.0	IA	IA	
57.6	7.3	32.5	1.73	1.80	13.2	IA	IA	
60.0	5.30	35.1	1.55	1.60	18.7	IA	IA	
62.8	12.0	30.0	2.02	2.00	9.0	IA	IA	
66.8	7.6	31.6	1.72	1.80	12.5	IA	IA	
68.0	12.0	29.3	1.90	1.90	9.7	IA	IA	
69.6	11.5	33.3	2.17	2.20	8.8	IA	IA	
71.2	20.0	28.5	2.34	2.40	5.0	IA	IA	
74.8	5.9	27.1	1.33	1.40	16.0	IA	IA	
77.6	5.6	25.0	1.22	1.26	17.4	CC	CC	

Explanation of Table Abbreviations
(G-R): Methodology developed by Gómez-Rivero
(M-V): Methodology developed by Mendoza and Valle
AC: Cavernous clayey voids
IA: Intergranular voids and high porosity
CC: Communicating cavernous voids
FF: Fracture voids
IB: Intergranular voids and low porosity
CA: Cavernous voids and high porosity
AF: Fractured clayey voids

A new geophysical log interpretation method has been applied that has demonstrated its effectiveness to evaluate dual porosity aquifers. This methodology allows the characterization of the internal structure of geologic formations and the definition of intervals with better aquifer characteristics. The method has been applied successfully in the karstic aquifer of the Northern Basin of Matanzas, Cuba.

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