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Matrix hydrodynamic properties of carbonate rocks from the Betic Cordillera (Spain)

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Abstract:

Laboratory tests performed on 181 rock samples from boreholes drilled in different areas of the Betic Cordillera allow us to calculate their hydraulic conductivity and open porosity values. Higher values are generally associated with Miocene calcareous sandstones, although hydraulic conductivity reaches its highest values in some isolated limestone and dolostone samples. Lower values were found in marly limestones and marbles. Specific yield ranged from 0 to 0·0798, with a mean value of 0·00579. A total of 79 samples did not release water during the specific yield test, while another 11 samples released water for more than 30 min. Such wide ranges of variation show the great diversity of behaviour that the matrix of the carbonate rocks can have, referring to water storage and transfer, and its influence on pollutants spread, for example. A weak relation between interconnected porosity and hydraulic conductivity was found. The relation between interconnected porosity and specific yield is slightly stronger, except in the case of the dolomites, where a high correlation was found. No dependence on depth was found for hydraulic conductivity and interconnected porosity. Copyright © 2004 John Wiley & Sons, Ltd.

KEY WORDS Betic Cordillera; carbonate rocks; open porosity; hydraulic conductivity; specific yield; relative drainability

INTRODUCTION

The hydraulic conductivity of rocks is the most important control of groundwater flow. It depends on the nature and connectivity of voids, and it varies largely with the scale of measurement, especially in rocks with secondary fracture or karstic porosity (Kiraly, 1975; Whitaker and Smart, 2000). Usually, large-scale tests are preferred to small-scale ones, due to logistic and/or financial limitations. But matrix porosity of carbonate aquifers is the main reservoir for solute transport and the main contributor to the specific yield in this type of aquifer (Zuber and Motyka, 1998), and these properties are of interest when characterizing them.

Matrix discontinuities may make up a substantial portion of the voids volume capable of storing water, as well as having a role at the beginning of karstification. With the aim of reducing this lack of knowledge in the carbonate materials of the Betic Cordillera, 181 cored rock samples were taken from boreholes, previously drilled for the construction of dams in the region, not according to any statistical approach. All the samples were taken from the core samples stored in the premises of the Catchment Authority; in other words, they were not collected by us as the boreholes were being drilled, and so no hydrogeological data are available about the boreholes or their characteristics (depth of the water table, for example).

The main objective of this paper is to characterize the matrix of the carbonate rocks from the Betic Cordillera from a hydrodynamic point of view, at the scale of the cored sample. This can help in developing conceptual models, in interpreting tracer tests, in analysing the transport of materials and in calculating the reserves

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for the aquifers of the region. We also want to try to characterize the eventual existence of matrix property variations with depth, as is frequently assumed.

METHODS

Before studying the hydraulic characteristics of the rock samples, these were carefully washed with water, to avoid the effects of the drilling method.

Rock samples were taken from research boreholes drilled for the construction of eight dams distributed over the eastern part of Andalucia (Figure 1). Three of them are built in the internal zone of the Betic Cordillera, another three are in the external zone, and the remaining two in Neogene intraorogenic basins, so the materials drilled by the boreholes cover a wide spectrum of ages (from Paleozoic to Cenozoic). The 181 samples were taken from depths of 1 m to 258 m. Of these, 98 samples were made of limestones or dolostones, 75 of calcareous sandstones, 6 of marly limestones and 2 of marbles. The diameter of the samples ranged from 46 to 47 mm, while their length was near 50 mm.

Open porosity was measured in a vacuum chamber; all the air from the sample was extracted and the space filled with water to weight the sample repeatedly. Thus, the volume of the interconnected pores is measured. Before putting the samples in the vacuum chamber they were dried in a stove at 105–110°C during 24 h. To

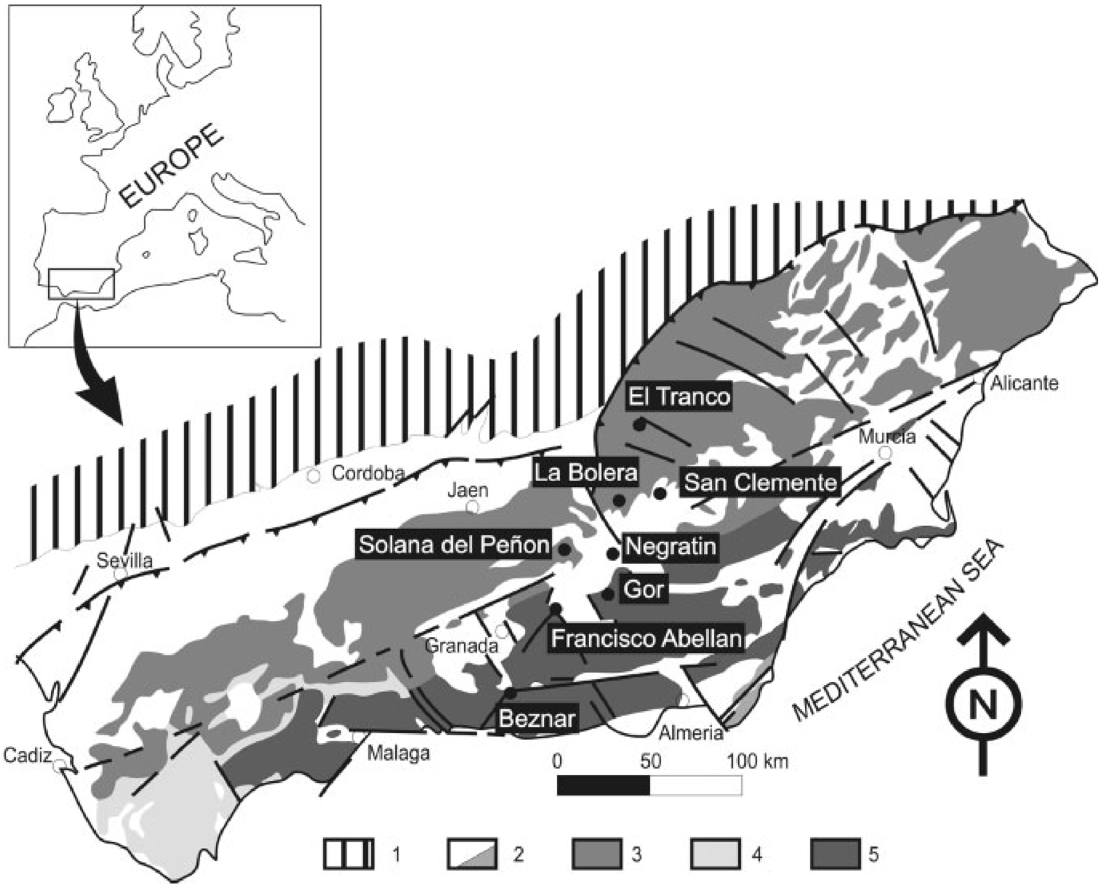

Figure 1. Geological location in the Betic Cordillera of the dams where rock samples have been taken for this study: 1, foreland; 2, neogene basins, vulcanism; 3, external zone; 4, flysch; 5, internal zone (modified from Sanz de Galdeano, 1993)

calculate the interconnected porosity (p_0), the following expression was used (Borczak *et al.*, 1990):

$$p_0 = \frac{G_n - G_s}{G_n - G_{nw}} \tag{1}$$

where G_n is the weight of the sample saturated with water, G_s is the weight of the sample dried at 105–110°C and G_{nw} is the weight of the sample saturated with water weighted in water, applying the Archimedes principle.

The method used for calculating the specific yield (S) is based on the centrifugation of the samples (Prill *et al.*, 1965). Because water drains slowly by gravity, a centrifuge was used to accelerate the process. The suction pressure affecting the sample due to centrifugal strength liberates part of the water content of the sample (the gravitational water), calculated with the following formula:

$$H = \frac{\left(\frac{2\pi n}{60}\right)^2 rh}{g} \tag{2}$$

where H is the suction pressure of the water from the matrix, expressed as metres in height of the water column, n is the number of revolutions per minute, r is the centrifugation radius (distance in metres from the centrifuge axis to the centre of gravity of the sample), h is the length of the sample in metres and g is the gravitational acceleration (9·81 m/s^2).

The natural conditions have been simulated using a suction pressure equivalent to a 10 m high water column. Establishing all the variables ($H = 98$ kPa and length of each sample), the number of revolutions required for each sample was calculated. The amount of water obtained by centrifugation allows us to calculate the specific yield (S):

$$S = \frac{V_w}{V_r} \tag{3}$$

where V_w is the water volume liberated by suction water equivalent to a 10 m high column (cm^3) and V_r is the rock volume (cm^3). The extraction pressure of the water simulated by centrifugation for small samples is equivalent to the maximum natural extraction pressure for water exerted by gravity in a stratum of thickness h.

The centrifugal acceleration (a) is expressed as:

$$a = wr^2 \tag{4}$$

where w is the angular velocity. From Equation (2), we can write:

$$\frac{H}{h} = \frac{a}{g} \tag{5}$$

where

$$a = \left(\frac{2\pi n}{60}\right)^2 r$$

from which we can calculate n (rpm) for each sample. According to Prill *et al.* (1965), the relationship between the percolation time of gravitational water in nature (T_n) and the centrifugation time (t) can be expressed as:

$$\left(\frac{T_n}{t}\right) = \left(\frac{a}{g}\right)^2 \tag{6}$$

All the samples were centrifuged for 30 min (t), which, depending on the length of the sample, would be equivalent to a percolation time under natural conditions (T_n) of between 660 and 940 days (from 2 to 2·5 years); 12 samples needed an extra time to free all the water they contained.

The relative drainability (S_0) is defined as:

$$S_0 = \frac{S}{p_0} \tag{7}$$

where S is the specific yield and p_0 the interconnected porosity. This coefficient depends on the pore diameter of the matrix as well as on the nature of the porosity (fissures, small capillary pores, etc.).

The hydraulic conductivity was measured using the method of Dulinski (1965). The samples were dried at 105–110 °C and then placed in an air permeameter. The expression used to calculate Darcy's permeability coefficient (K_g) is:

$$K_g = \frac{2Q_0 p_0 L\eta}{F(p_1^2 - p_2^2)} \tag{8}$$

where Q_0 is the gas flow (cm^3/s), p_0 is the atmospheric pressure (atm), L is the sample length (cm), h is the viscosity coefficient of the gas, F is the area of the section of the sample (cm^2), p_1 is the gas pressure before passing through the sample (atm) and p_2 is the pressure after passing through the sample (atm).

The coefficients obtained were then recalculated for water at 10 °C (K_{10}), according to the equation:

$$K_{10} = K_g \frac{\gamma}{\eta} \tag{9}$$

where g is the specific weight of the water, so this can be expressed as:

$$K_{10} = 7{\cdot}66 \times 10^{-6} {\cdot} K_g \tag{10}$$

Nevertheless, the hydraulic conductivity values obtained in this way do not coincide with those obtained by natural means using water. Therefore, the Klinkenberg correction coefficient must be considered. This coefficient depends on many factors and is inherent to each type of rock. As a consequence of this, we know that K_g and the recalculation for water K_{10} are in fact lower, especially in low hydraulic conductivity samples (Klinkeberg, 1941).

RESULTS

The samples were described prior to their analysis. According to their macroscopic structure and texture characteristics, five groups of samples were distinguished: bioclastic calcareous sandstones (75), limestones (68), dolostones (30), marly limestones (6) and marbles (2). Table I shows the main statistical parameters of the studied parameters.

Table I. Basic statistics

	p_0	S	S_0	k (m/s)
Count	181	181	181	181
Average	0·05277	0·00579	0·0758	$3{\cdot}24 \times 10^{-7}$
Variance	0·002841	0·000138	0·0160	$1{\cdot}58 \times 10^{-11}$
Standard deviation	0·05330	0·0118	0·126	$3{\cdot}98 \times 10^{-6}$
Minimum	0·004458	0·0	0·0	$2{\cdot}71 \times 10^{-12}$
Maximum	0·2091	0·0798	0·666	$5{\cdot}35 \times 10^{-5}$
Range	0·2046	0·0798	0·666	$5{\cdot}35 \times 10^{-5}$
Stnd. skewness	8·805	17·1	12·6	73·7
Stnd. kurtosis	4·001	31·7	15·5	496
Coeff. of variation	101%	203%	167%	1230%

Interconnected porosity

Interconnected porosity shows a wide range of variation. The values range from 0·00 446 to 0·209, with a mean of 0·0528, a standard deviation of 0·0533 and a coefficient of variation of 101% (Table I). The highest porosity was measured for the calcareous sandstones (Table II), while a lower porosity was found in the dolostones, although the lowest mean value was that for the marbles. The distribution of values for interconnected porosity is not homogeneous; the limestone and dolostone distributions are quite similar, although the limestones show more separated outliers (Figure 2). The distribution that is more homogeneous is that for the marly limestones, but there are only six samples. The calcareous sandstone distribution is shifted to higher porosity values with respect to the other samples.

The mean interconnected porosity for the calcareous sandstones, 0·0846, is higher than that for the limestones (0·0318), which is slightly higher than that for the dolostones (0·0296). Lower mean values were obtained for marbles (0·0094) and for marly limestones (0·0223).

Specific yield

The specific yield of the 181 samples ranged from 0 to 0·0798 with a mean value of 0·00 579, a standard deviation of 0·0118 and a coefficient of variation of 203%. A total of 79 samples did not release any water during the specific yield test, including the two marble and the eight marly limestone samples. The distributions are quite similar for the other groups of samples (Figure 3), they all show a great deviation to the left side due to the abundance of zero values. The highest value was reached in a dolostone sample. The mean value for the dolostone group is higher (0·00 724). The mean values for calcareous sandstones (0·00 640) and limestones (0·00 517) are slightly smaller.

The dynamics of this test provides very interesting information. Eleven of the samples took more than 30 min (the equivalent of from 2 to 2·5 years of natural percolation) to free all the water they contained (Table III). Seven of them were limestones, three calcareous sandstones and only one dolostone. However, the behaviour of the samples is not homogeneous, even for the same lithology. Figure 4 shows the dynamics

Table II. Basic statistical characteristics for the four studied parameters in the five sample groups considered: 1, Neogene bioclastic calcareous sandstones; 2, Mesozoic limestones; 3, Mesozoic dolostones; 4, Mesozoic marly limestones; 5, Paleozoic marbles. p_0, interconnected porosity; S, specific yield; S_0, relative drainability; k, hydraulic conductivity

Parameter		1	2	3	4	5
No.	samples	75	68	30	6	2
p_0	min	0·0137	0·005739	0·004458	0·0174	0·006562
	max	0·2091	0·1782	0·1198	0·0266	0·01223
	mean	0·0846	0·031796	0·02963	0·0223	0·009396
	stnd. dev.	0·0612	0·036497	0·02153	0·004	0·004008
S	min	0	0	0	0	0
	max	0·04677	0·0485	0·0798	0	0
	mean	0·00640	0·005165	0·00724	0	0
	stnd. dev.	0·01174	0·0102	0·01856	0	0
S_0	min	0	0	0	0	0
	max	0·2699	0·6175	0·6659	0	0
	mean	0·0505	0·0882	0·131177	0	0
	stnd. dev.	0·0652	0·1432	0·18463	0	0
k	min	$2{\cdot}71 \times 10^{-12}$	$6{\cdot}51 \times 10^{-12}$	$4{\cdot}85 \times 10^{-12}$	$9{\cdot}59 \times 10^{-12}$	$7{\cdot}4 \times 10^{-12}$
	max	$1{\cdot}83 \times 10^{-7}$	$5{\cdot}35 \times 10^{-5}$	$1{\cdot}21 \times 10^{-6}$	$1{\cdot}82 \times 10^{-10}$	$3{\cdot}28 \times 10^{-10}$
	mean	$1{\cdot}09 \times 10^{-8}$	$8{\cdot}03 \times 10^{-7}$	$1{\cdot}07 \times 10^{-7}$	$5{\cdot}37 \times 10^{-11}$	$1{\cdot}68 \times 10^{-10}$
	stnd. dev.	2·912	3·175	4·016	0·978	2·681

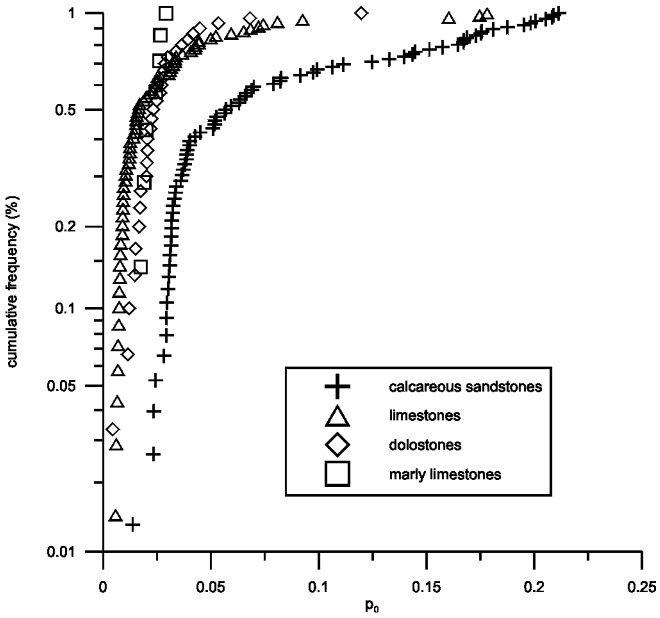

Figure 2. Cumulative frequency plot of the interconnected porosity

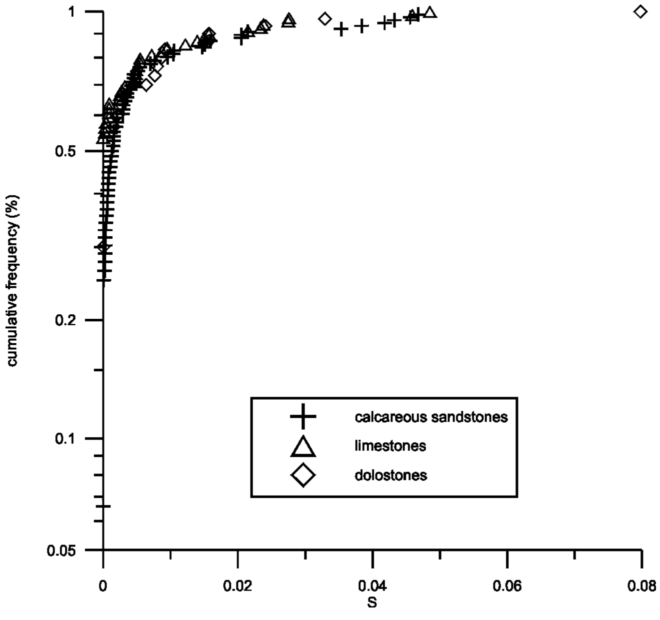

Figure 3. Cumulative frequency plot of the specific yield

of the drainage for the sample from each lithology that took a longer time to release all its water. It shows the variation of the (S_t/S) ratio versus time, where S_t is the instantaneous specific yield and S the total specific yield. The dolostone sample released all its water in 40 min, while the calcareous sandstone took 120 min and the limestone more than 180 min to free their water. It is evident that the pores in these calcareous sandstone and dolostone samples are bigger than those in the limestone sample, as the two former

Table III. Water volume released by representative samples with increasing centrifugation time. The lithology of each sample is noted (C.S.: calcareous sandstone, D: dolostone, L: limestone)

Lithology	Sample	Centrifugation time (min)													V_{total}
		1	3	5	10	15	20	30	40	60	90	120	150	180	
C.S.	B-2	0·08	0·1	0·11	0·12	0·13	0·14								0·14
C.S.	B-16	0·05													0·05
C.S.	B-18	0·01													0·01
C.S.	B-22	0·04	0·07	0·09	0·1										0·1
C.S.	B-23	0·01													0·01
C.S.	B-31	0·19	0·26	0·29	0·31	0·33	0·35								0·35
C.S.	B-47	0·02	0·04	0·05	0·06	0·07									0·07
C.S.	B-53	0·05	0·09	0·11	0·12										0·12
C.S.	H-14	0·36	0·41	0·52	0·6	0·68	0·74	0·87	0·93	1·02	1·07	1·1			1·1
C.S.	H-16	0·02	0·04	0·06	0·07	0·08									0·08
C.S.	H-19	0·12	0·14	0·16	0·19	0·21	0·23	0·28	0·3	0·32	0·36	0·37			0·37
C.S.	H-22	0·03	0·07	0·09	0·13	0·21	0·25	0·33	0·36	0·42	0·43	0·45			0·45
C.S.	H-27	0·09	0·15	0·2	0·22										0·22
D	J-14	0·91	1·09	1·14	1·19	1·2									1·2
D	J-18	0·17	0·21	0·25	0·29	0·3	0·31	0·32							0·32
D	J-20	0·22	0·29	0·36	0·52	0·55	0·57	0·58	0·59						0·59
L	H-59	0·46	0·54	0·56	0·57	0·58									0·58
L	J-5	0·48	0·52	0·55	0·57										0·57
L	J-22	2·93	4·16	4·41	5·08	5·43	5·58	5·7	5·76	5·79	5·82	5·83	5·87	5·88	6
L	J-30	0·79	1·07	1·27	1·38	1·45	1·5	1·53	1·56	1·57	1·58				1·58
L	J-39	0·01	0·02	0·03											0·03
L	J-40	0·02	0·03	0·04											0·04
L	J-41	0·08	0·12	0·16	0·18	0·22	0·24	0·26	0·27						0·27
L	J-42	0·6	0·88	0·98	1·08	1·14	1·18	1·2	1·22	1·23					1·23
L	J-47	2·7	3·1	3·3	3·58	3·7	3·8	3·86	3·92	3·94	3·96				3·96
L	J-52	0·76	1·14	1·32	1·5	1·61	1·67	1·7	1·73	1·74	1·75	1·8			1·8
L	J-53	1·74	2·2	2·37	2·53	2·59	2·66	2·7	2·72	2·73					2·73

released almost 90% of their water in 30 min, while the latter took more than 60 min to release 90% of its water.

Relative drainability

As relative drainability is equal to the quotient between the specific yield and the interconnected porosity, 79 samples share a 0 relative drainability. The mean value is 0·0758, the standard deviation is 0·126 and the coefficient of variation is 167%. The maximum value (0·666) was reached in a dolostone sample. Dolostones show a higher mean value (0·131). The limestone mean value (0·0882) is higher than that for calcareous sandstones (0·0505). The slope for the distribution of the calcareous sandstones is higher than those for limestones and dolostones (Figure 5), which means that the latter two have a wider range than the former.

Hydraulic conductivity

The hydraulic conductivities of the rock samples from the Betic Cordillera range from $2{\cdot}71 \times 10^{-12}$ to $5{\cdot}35 \times 10^{-5}$ m/s, with a geometric mean of $4{\cdot}25 \times 10^{-10}$ m/s, a standard deviation of $3{\cdot}98 \times 10^{-6}$ and a coefficient of variation of 1230%. The minimum value was obtained for a calcareous sandstone sample, while the maximum value was found in a limestone sample. The distributions for all the rock types are quite similar, except for the marly limestones, that show a quite narrow range (Figure 6). The higher geometric

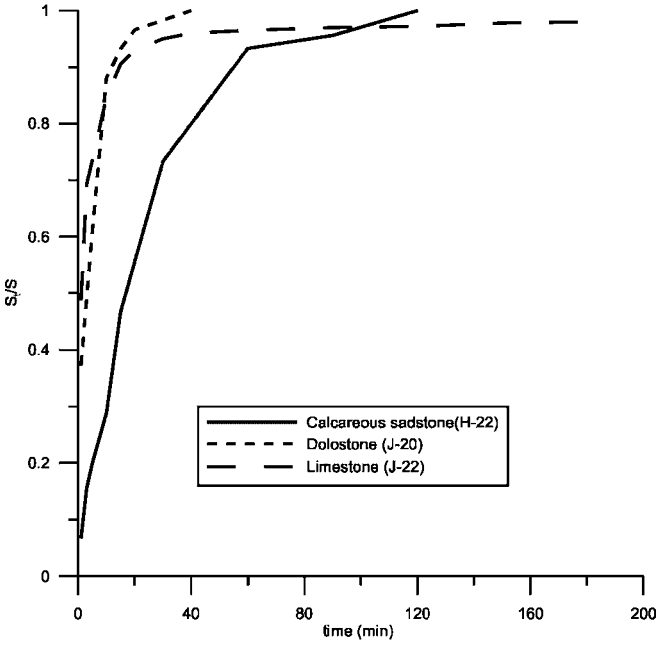

Figure 4. Dynamics of drainage (S_t/S) for the sample of each lithology that released water during a longer time (S_t is the instantaneous specific yield and S the total specific yield)

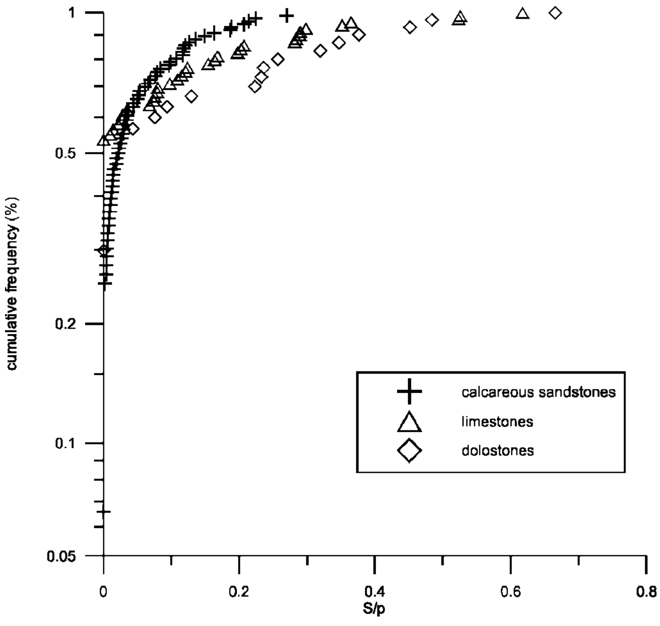

Figure 5. Cumulative frequency plot of the relative drainability

mean values were obtained for the dolostones (5·52 × 10^{-10}) and the limestones (5·10 × 10^{-10}), while the lower mean values were found in the marly limestones (3·45 × 10^{-11}) and the marbles (1·68 × 10^{-10}). The geometric mean of the hydraulic conductivity in the calcareous sandstones is 4·19 × 10^{-10}. This means that

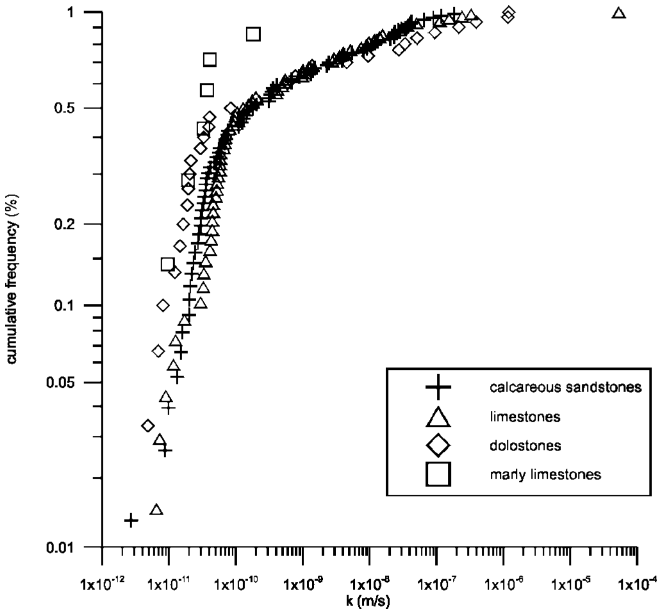

Figure 6. Cumulative frequency plot of the hydraulic conductivity

the hydraulic conductivity in the carbonate rocks from the Betic Cordillera is highly dependent on the presence of fractures and fissures.

DISCUSSION

Correlation between hydrogeological parameters

Despite the weak relationship found between interconnected porosity and hydraulic conductivity, two branches can be distinguished in the distribution of the samples in the p_0–k plot (Figure 7). In the first branch, calcareous sandstones dominate, while the other one is composed mainly of limestones and dolostones. This is due to the fact that the samples from the first branch have smaller pores and the water is attracted with a higher strength than in the samples from the second branch, whose pores may be enlarged as a consequence of dissolution and the presence of small fractures. A potential function was fitted to each group of samples, even if the correlation coefficients are not too high. The function fitted to the calcareous sandstones is $k = 10^{-6}\cdot(p_0)^{2\cdot872}$ ($R^2 = 0\cdot5218$), while for the limestones it is $k = 2 \times 10^{-5}\cdot(p_0)^{2\cdot7035}$ ($R^2 = 0\cdot5615$) and for the dolostones $k = 0\cdot0282\cdot(p_0)^{4\cdot7982}$ ($R^2 = 0\cdot5156$).

The separation of the branches is less clear when comparing p_0 and S (Figure 8), even if the calcareous sandstones group can be distinguished from the one made up of limestones and dolostones. Samples from this last group have lower interconnected porosity for specific yields of the same order of magnitude. When plotting relative drainability versus open porosity (Figure 9), the separation of the groups is confirmed: there is a group with high open porosity and a group with high drainability. In this case, the functions fitted are linear. The best fits for the calcareous sandstones ($S = 0\cdot143p_0 - 0\cdot0057$) and the limestones ($S = 0\cdot1914p_0 - 0\cdot0009$) do not show high determination coefficients ($R^2 = 0\cdot5559$ and $R^2 = 0\cdot4679$, respectively). On the other hand, the relation found between the interconnected porosity and the specific yield in the dolomites is relevant ($S = 0\cdot7099p_0 - 0\cdot0138$, $R^2 = 0\cdot9289$).

Figure 10 shows the relationship between specific yield and hydraulic conductivity. The trend is similar for the three groups of samples, although higher values are found in limestone and dolostone samples.

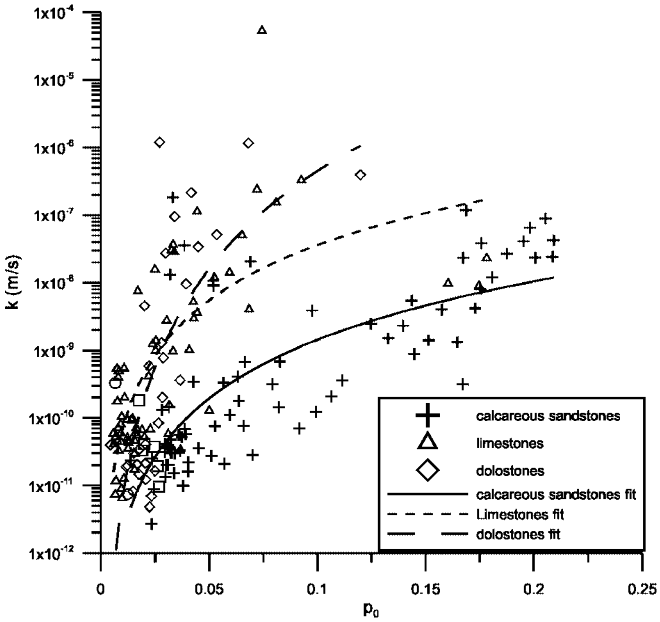

Figure 7. Hydraulic conductivity–open porosity plot

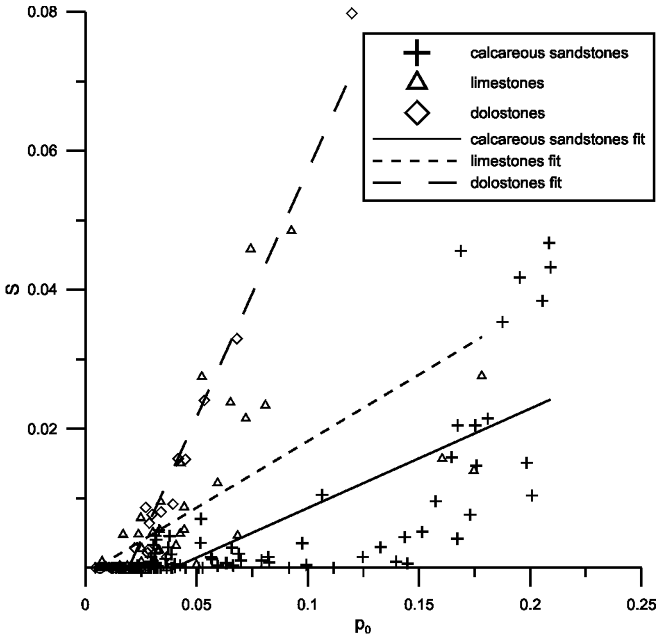

Figure 8. Specific yield–open porosity plot

Exponential functions were fitted to these distributions. A nearly good fit was found for the limestones ($k = 10^{-10}\ e^{253 \cdot 09S}$, $R^2 = 0 \cdot 6626$), while those for the dolostones ($k = 2 \times 10^{-10}\ e^{165 \cdot 74S}$, $R^2 = 0 \cdot 4286$) and the calcareous sandstones ($k = 10^{-10}\ e^{166 \cdot 64S}$, $R^2 = 0 \cdot 451$) do not show high determination factors.

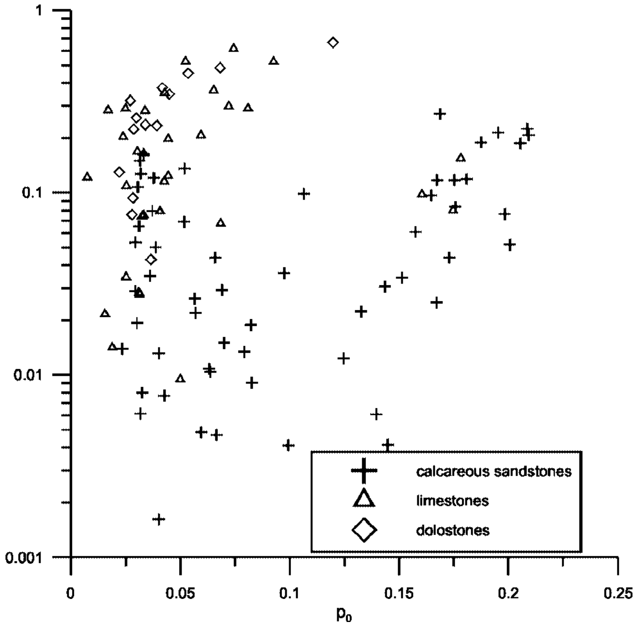

Figure 9. Relative drainability–open porosity plot

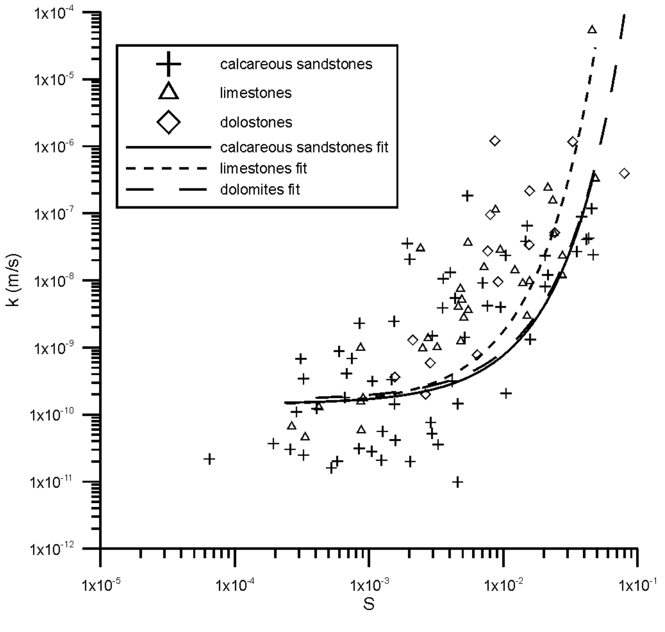

Figure 10. Hydraulic conductivity–specific yield plot

Variation with depth

Most of the karstic hydrogeology books apply a karstic aquifer model in which the interconnected porosity and the hydraulic conductivity reach their higher value in the fluctuation zone of the water table and decrease with depth, reflecting an atmospheric origin for the CO_2 responsible for the karstification (Bögli, 1980; White,

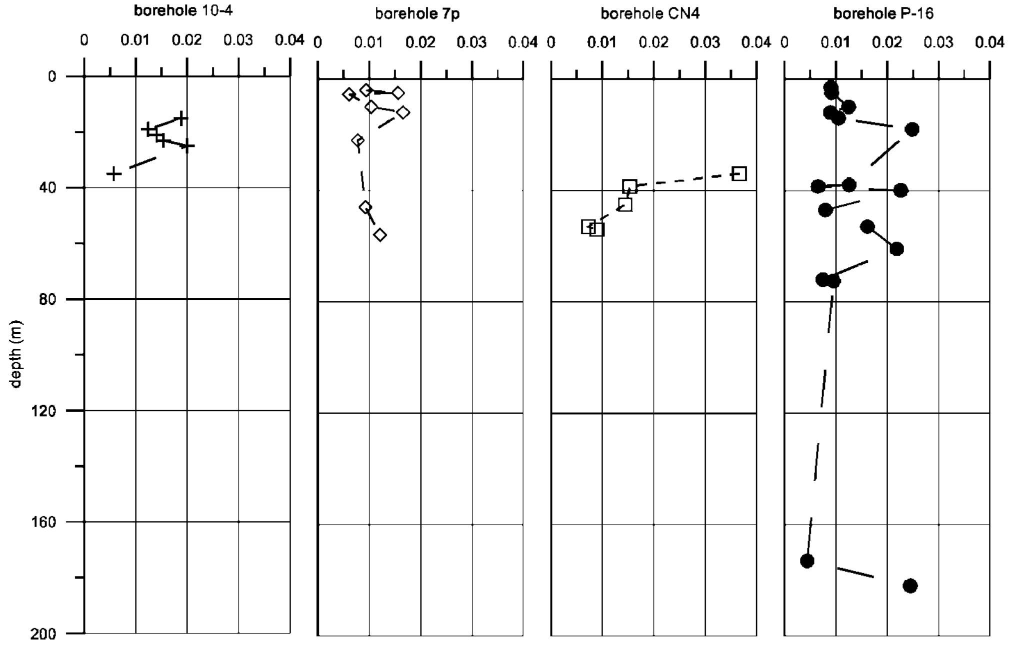

Figure 11. Interconnected porosity vs depth (m) for the samples from four boreholes drilled for the construction of the San Clemente dam

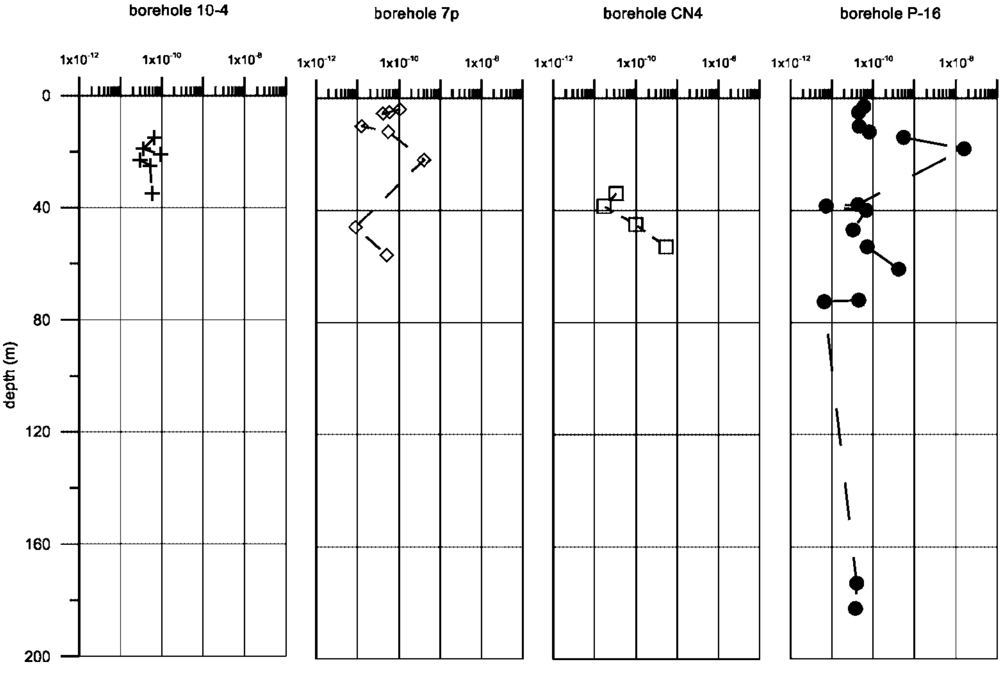

Figure 12. Hydraulic conductivity (m/s) vs depth (m) for the samples from four boreholes drilled for the construction of the San Clemente dam

1988; Ford and Williams, 1989). With the aim of evaluating the possible relation of the matrix properties with depth, cretaceous limestone samples from four boreholes drilled for the construction of the San Clemente dam were plotted against depth. When comparing interconnected porosity with depth (Figure 11), big fluctuations are detected, so it is not possible to find any relation between these two parameters. In fact, the only thing that can be observed is that there are alternating strips with higher and lower porosity, surely because of small compositional differences or due to the presence of small fissures and fractures.

In the case of hydraulic conductivity, no relation with depth was found (Figure 12). Moreover, in some places the behaviour is opposite to that of porosity. We can infer from this that no relation exists between depth and hydraulic conductivity or interconnected porosity.

FINAL CONSIDERATIONS

Although it is usually ignored, a carbonate rock matrix could play a very important role in solute transport and water storage Motyka *et al*., 1998.

Hydraulic conductivity and interconnected porosity ranges for the carbonate rocks from the Betic Cordillera are wide. In general, calcareous sandstones (most of them from the Miocene age) have a greater interconnected porosity, but limestones and dolostones show a higher hydraulic conductivity. Marly limestones and marbles show interconnected porosity and hydraulic conductivity much lower than the other groups. Specific yield also shows a great range of variation from samples that did not release any water to samples that released water for more than 30 min.

A weak relationship between interconnected porosity and hydraulic conductivity was found. The relationship between interconnected porosity and specific yield is slightly stronger, except in the case of the dolomites, where a high correlation was found. No dependence on depth was found for hydraulic conductivity and interconnected porosity. This is contrary to what might be expected, in the sense of a possible decrease with depth, as has been described for karstification at a borehole scale in the Dinaric karst (Milanovic, 1981).

Lastly, we want to highlight the importance of this type of investigation in terms of a real understanding of the physical environment, and of the rock matrix in particular; to cite an area of interest, to have an understanding and for the simulation of the propagation of pollutants in media of double or triple porosity (primary, discontinuities in the matrix, karstic conduits and cavities) with the possibility of exchange between the less transmissive medium and that with a greater hydraulic conductivity, and the influence that the matrix will have in decontamination. In this scheme of things, we have undertaken the study of pollution caused by a closed sanitary landfill site situated over carbonate rocks in the region of Málaga (South Spain), for which there were numerous core samples (Vadillo, 2003)

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