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Estimation of rock mass permeability using variation in hydraulic conductivity with depth: experiences in hard rocks of Western Turkey

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Abstract

The determination of the permeability of fractured rocks is one of the focal points in engineering projects. Many methods have been developed for the direct in-situ determination of the hydraulic parameter; nevertheless, especially in the preliminary stages of the rock mass characterization, empirical correlations are used to estimate the permeability of the rocks. The present study proposes a relationship between depth and permeability of rock mass useful for an initial hydraulic characterization of fractured media. For this purpose, results of core drilling, injection tests and geophysical prospecting carried out in fractured rocks of Western Turkey were considered. For these hard rocks, mainly andesites and secondly metamorphites, a decrease of rock mass permeability with depth is evident from the results of injection tests. Within the depth of investigation (the first hundred meters), the hydraulic conductivity shows an exponential declining trend with the depth, and depends on the surface value of the hydraulic parameter. No correlation is evident between discontinuity spacing and depth, nor between *RQD* and depth. The applicability of the relationship found requires a hydro-structural homogeneity of the rock mass that can be verified through inexpensive geological survey and geophysical prospecting.

Keywords: Hydraulic conductivity, Rock mass, Injection test, Discontinuity spacing, Hard rock

1. Introduction

The determination of the permeability of fractured rocks is one of the focal points in engineering projects concerning dams, tunnels, quarries and mines. The complexity of the topic is related to the heterogeneity and anisotropy of rock masses. Many methods have been developed for the direct in-situ determination of the hydraulic parameter, such as pumping tests, injection tests, interference tests and hydraulic tomography (e.g., Kruseman and de Ridder 1994; Shapiro and Hsieh 1998; Illman and Neuman 2000; Tiedeman and Hsieh 2001; Zhu and Yeh 2006). These investigations, which are the most reliable for the hydraulic characterization of rock masses, are not always easy to perform because time and cost consuming. In the preliminary stages of the rock mass characterization, empirical correlations are often used to estimate the permeability of rocks and its variation with depth.

Among these, some researchers have correlated the rock mass permeability to the common rock mass quality indices, such as *RQD* (Rock Quality Designation) (El-Naqa 2001; Cha et al. 2006; Jiang et al. 2009; Qureshi et al. 2014). However, *RQD* does not include information of the discontinuity aperture, which has a great influence on the permeability of the rock, as also demonstrated by analytical relations (e.g., Sen 1996).

Other researchers have analyzed the effect of stresses on rock masses permeability, founding empirical relations between the discontinuity permeability and confining pressure. Increasing the confining pressure with depth, a decrease of rock mass permeability with depth is to be expected (e.g., Carlsson and Olsson 1977, 1993; Lee and Farmer 1993; Zhao 1998; Meng et al. 2011; Zhang 2013). Accordingly, several studies have shown that the rock mass permeability decreases with depth according to different empirical relationships (e.g., Louis 1974; Snow 1968). Based on in-situ permeability tests and fracture frequency determination, Snow (1968) found that discontinuity spacing generally increases and aperture decreases with depth. Snow (1968, 1969) and other researchers (see for example, Zhang 2013 and Lee and Farmer 1993, and the literature cited therein) agree that the decrease of rock mass permeability with depth is mainly due to the decrease of discontinuity aperture with depth.

The present study is addressed to analyze the relationships among discontinuity spacing, depth and permeability of rock mass. The purpose of this paper is i) to verify the influence of spacing on the rock mass permeability, and ii) to derive a relationship between permeability and depth, useful for a preliminary hydraulic characterization of fractured rocks. For this purpose, data of boreholes drilled in fractured rocks of Western Turkey were considered, analyzing results of core drilling, injection tests and geophysical prospecting.

2. Approach, materials and methods

The approach used in this study has considered the results of the hydraulic characterization of fractured rocks through in-situ tests and the analysis of the discontinuity spacing, main geometric characteristic of discontinuities detectable on core drilling. These characterizations have been framed in a more significant volume of the rock mass, using the results of geophysical prospecting.

In-situ investigations were carried out in fractured rocks in the Kozak area, Western Turkey. Recovered cores and hydraulic tests concerned six vertical boreholes with a depth ranging from 85 to 140 m, located within an area of about 1 km^2 as shown in Figure 1. Five boreholes penetrated volcanic rocks, one borehole intersected also metamorphic rocks.

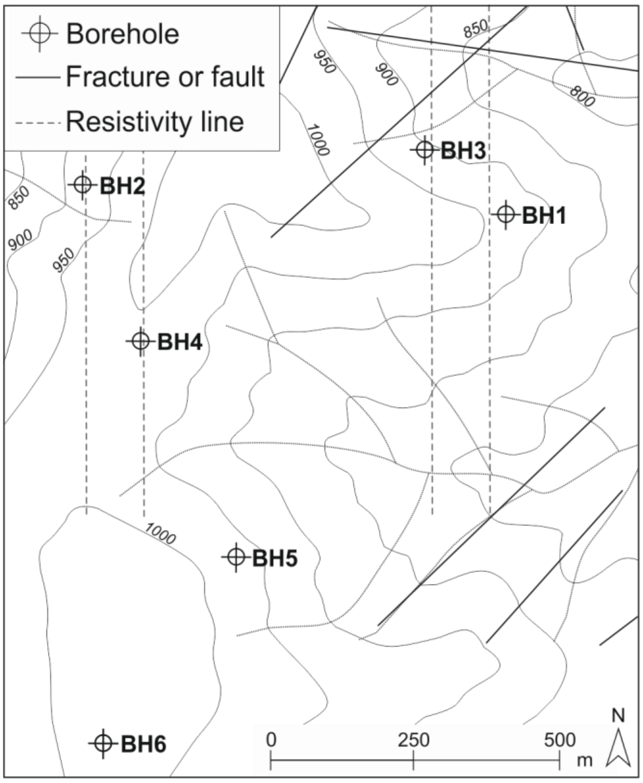

Fig. 1 Location of the boreholes and resistivity lines

Volcanic rocks belong to Lower-Middle Miocene volcanic association and are andesitic in composition, constituted by plagioclase, horneblende, biotite and sanidine phenocrysts with microlithic and rarely cryptocrystalline matrix. Metamorphic rocks constitute the Triassic basement of the volcanic succession and include low-degree metamorphites, mainly constituted by micaschists. Both formations are intensely fractured (Altunkaynak and Yilmaz 1998; Okay and Goncuoglu 2004).

During the drilling, injection tests in the single borehole, also known as packer tests (or Lugeon tests), were carried out, according to the prescribed procedures (e.g., US Department of the Interior Bureau of Reclamation 2001). This test represents the simpler and most widespread method of characterizing the in-situ permeability of fractured media, assuming the rock surrounding the borehole as a locally uniform porous continuum (e.g., Neuman 2005; Jiang et al. 2009).

Specifically, the injection tests were conducted by isolating 5 m sections of the borehole with inflatable packers and injecting water. For each section, at least 5 pressure steps were performed, each one lasting 10 min. The value of pressure on the manometer was increased and decreased from 0.1 up to 1.0 kN/m^2. The fluid-injection rate was monitored for each step. Hydraulic head *h* at the test section was determined for each step considering the pressure value measured at the manometer, the height of the manometer, the weight of the water column standing in the pipe above the test section and friction losses along the pipe. The linearity of the relationship between discharge injected *q* and hydraulic head *h* was preliminary evaluated for each test section, in order to check the laminar flow conditions (Louis and Maini 1970). The values of *q* and *h* of the first and lower pressure step appeared to meet the laminar flow conditions; in this case, *q* was less than 3 L/min and injection pressure was less than the effective overburden pressure. Under these conditions, the hydraulic conductivity of the test section k_d can be estimated by the Thiem equation (e.g., Ziegler 1976), which can be approximated by (e.g., Jiang et al. 2009):

$$k_d = \frac{q}{2\,\pi\,h\,l} ln \frac{l}{r_0} \qquad (1)$$

where *l* is the length of the injection section and r_0 is the borehole radius.

Measurements of core lengths were carried out during the drillings, together with the core recovery percentage. The core pieces were measured along the centerline, trying to avoid the measurement of core breaks caused by the drilling process. The discontinuity spacing *s* was measured as the distance between the points of discontinuities intersecting the vertical line of the drilling. The *RQD* was also determined through the recovered cores (Deere 1964) on 5 m intervals of drilling length, in alignment with the injection test sections. For the same intervals, the mean discontinuity spacing s_m and the mean number of discontinuities per meter *f* (i.e., $f = 1/s_m$) were determined.

In the same area of the tested boreholes, an electrical resistivity survey was conducted (Resistivity Survey Report ECC, Ankara 2013; unpublished technical report). Resistivity measurements were acquired along 10 lines (1.0-1.5 km long) through pole-dipole configuration, using IRIS Elrec Pro Receiver and Walcer KW10 Transmitter System. Current electrodes and potential electrodes were spaced 25 m intervals along the profiles. The 2D inverse resistivity models of the subsurface was obtained from the input resistivity data, using inversion code of RES2DINV. Four of the six tested boreholes fall exactly on the resistivity lines (Fig. 1).

3. Results

All boreholes crossed the fissured layer of hard rocks that do not comprise a weathered mantle in the study area. As shown in Figure 2, the percentage of core recovery was generally higher than 90 %, except for the boreholes BH2 and BH6. All boreholes penetrated andesitic rocks, the borehole BH6 reached the fissured metamorphic substrate of volcanic rock at depth greater than 30 m.

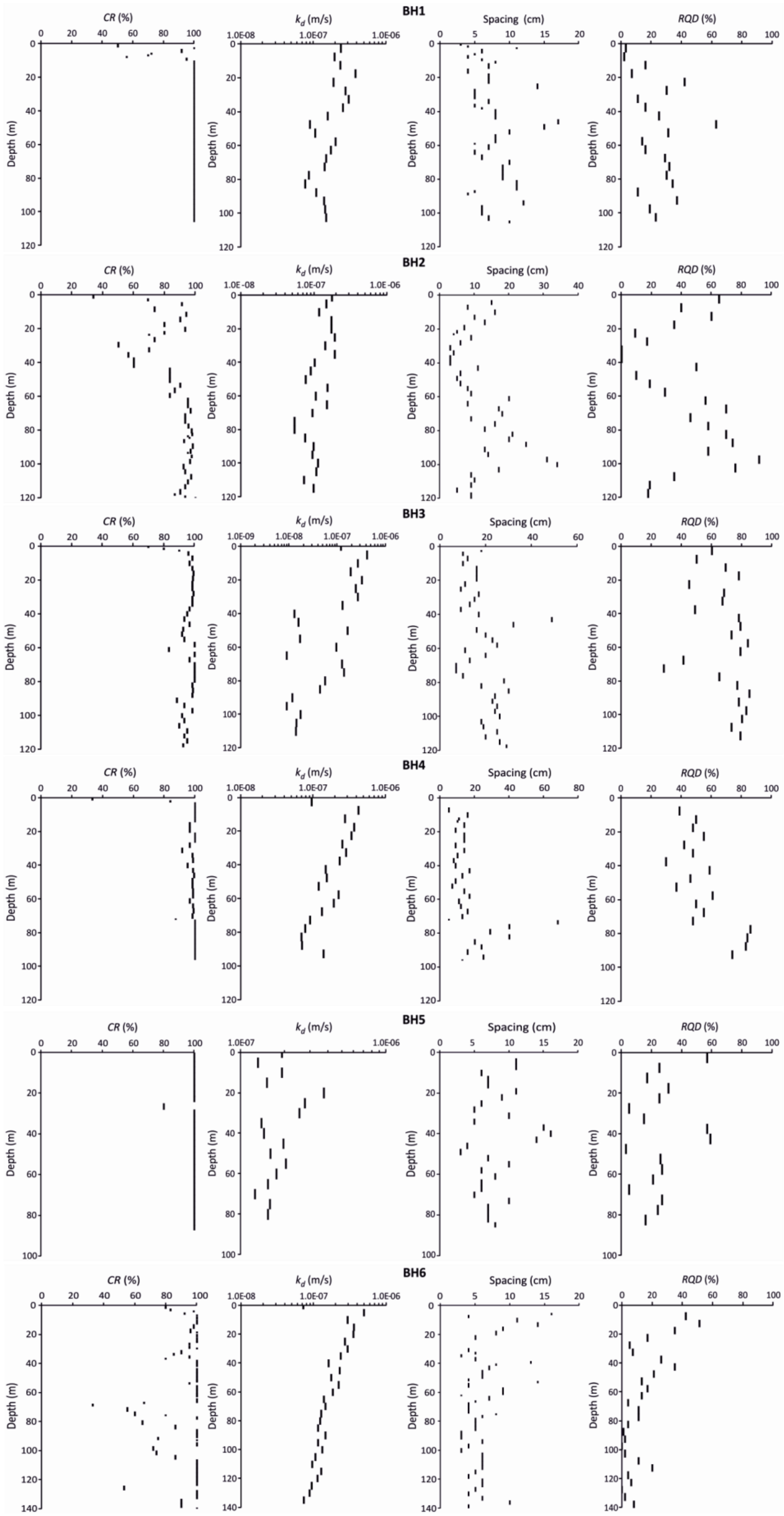

Fig. 2 Plots of core recovery percentage (*CR*), hydraulic conductivity (k_d), spacing and *RQD* measured in each borehole

132 injection tests were performed during the drilling of six boreholes up to 140 m depth, 109 test sections involved the volcanic rocks and 23 test sections involved the metamorphic rocks. For each test section of 5 m length, k_d was calculated using the equation (1) under the previously specified assumptions. The results of the tests for each borehole are shown in Figure 2, summary statistics are reported in Table 1. The frequency distribution of the k_d-values of all the tests is shown in Figure 3.

Table 1 Statistics of hydraulic conductivity data from injection tests

Borehole	Depth (m)	N tests	Rock	Arithmetic mean (m/s)	Standard dev. (m/s)	Coefficient of variation (%)	Geometric mean (m/s)
BH1	105	21	Andesite	1.81×10^{-7}	7.82×10^{-8}	43.2	1.66×10^{-7}
BH2	120	24	Andesite	1.18×10^{-7}	4.19×10^{-8}	35.5	1.11×10^{-7}
BH3	115	23	Andesite	1.17×10^{-7}	1.17×10^{-7}	100	5.86×10^{-8}
BH4	95	19	Andesite	1.94×10^{-7}	1.07×10^{-7}	55.2	1.67×10^{-7}
BH5	85	17	Andesite	1.87×10^{-7}	6.30×10^{-8}	33.7	1.79×10^{-7}
BH6	140	28	Andesite/metam.	1.81×10^{-7}	1.02×10^{-7}	56.4	1.58×10^{-7}
All boreholes		132		1.61×10^{-7}	9.40×10^{-8}		1.29×10^{-7}

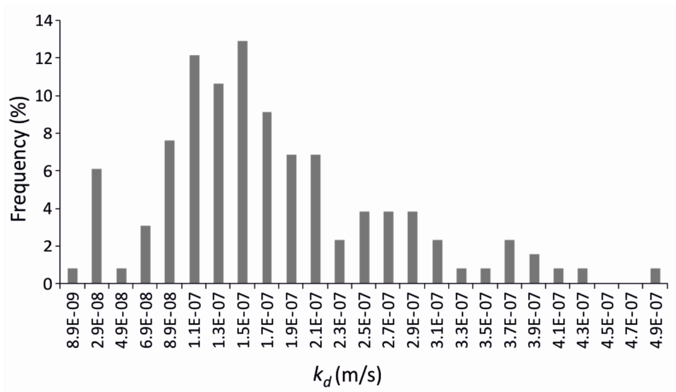

Fig. 3 Frequency distribution of the hydraulic conductivity k_d obtained from 132 injection tests

The mean value of k_d for each borehole little differs from the standard deviation, and comparing the six boreholes it falls within a narrow range (from 1.17 and 1.94 $\times10^{-7}$ m/s) (Table 1). The coefficient of variation (i.e., the ratio between standard deviation and arithmetic mean) is between 30 and 60 %, with the exception of BH3, which shows a higher variability (as also evident in Fig. 2) with a standard deviation equal to the mean. Considering all 132 tests, k_d varies over two orders of magnitude, from 10^{-8} and 10^{-7} m/s (Fig. 3) and the mean value, standard deviation and geometric mean are 1.61×10^{-7} m/s, 9.40×10^{-8} m/s and 1.29×10^{-7} m/s, respectively (Table 1).

A total of 3905 measurements of discontinuity spacing were taken during the 660 m total length of drilling. The results of measurements concerning each borehole are shown in Figure 2. The mean value of s for each borehole is approximately equal to the standard deviation, and it varies from 0.06 and 0.16 m. The frequency distribution of all measurements is reported in Figure 4.

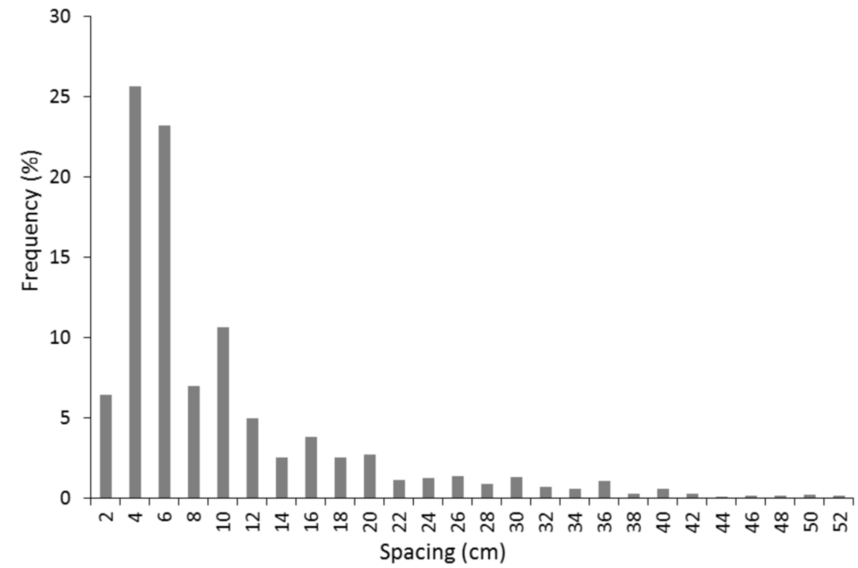

Fig. 4 Frequency distribution of all the 3905 spacing measures

The *RQD* values determined on 5 m intervals in each borehole are shown in Figure 2.

To examine the relationship between hydraulic conductivity and depth, a first processing included all k_d data. As shown in Figure 5, a decrease in k_d with depth seems to be present, although the relationship is strongly affected by the permeability variation among the different boreholes (Fig. 2). A further processing synthetized the hydraulic conductivities of the all boreholes (k_d, Fig. 2) with one arithmetic mean for each 5 m intervals of depth (k_{dm}). The plot of k_{dm} versus depth and the result of the regression analysis are shown in Figure 6. The general trend of k_{dm}-decrease with depth d is here clearer than in Figure 5, and can be represented by the following equation:

$$k_{dm} = 2.75 \times 10^{-7} e^{-0.0093d} \quad (2)$$

where k_{dm} is in m/s and d in m. The coefficient of determination for the equation (R^2) is 0.794, the RMSE (i.e., root-mean-square error) is 4.04×10^{-8} m/s, corresponding to a normalized RMSE of 17 %. Figure 6 and equation (2) show that k_{dm} varies over two orders of magnitude (from 10^{-8} and 10^{-7} m/s) and tends to 3×10^{-7} m/s towards the surface (i.e., for d = 0). Further regressions between k_{dm} and d showed lower fit statistics. If the intercept of equation (2) (2.75×10^{-7} m/s) is replaced by then mean ± standard deviation of the measured k_d in the first 10 m of depth ($2.24\times10^{-7} \pm 1.40\times10^{-7}$ m/s), it results that about 80 % of the values of k_d of Figure 5 falls between the two curves.

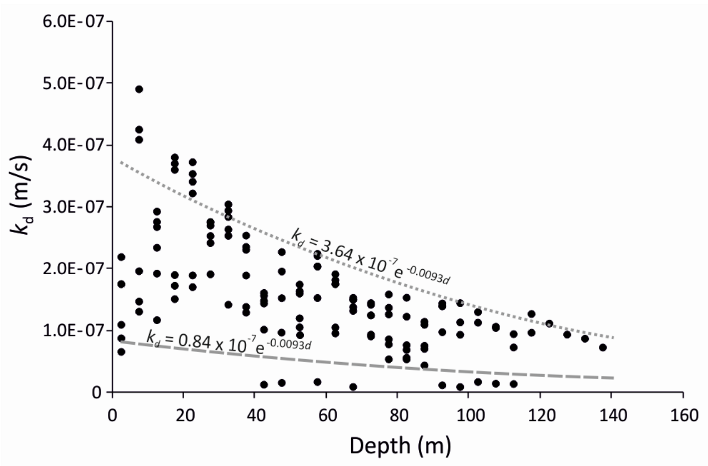

Fig. 5 Plot of k_d versus depth

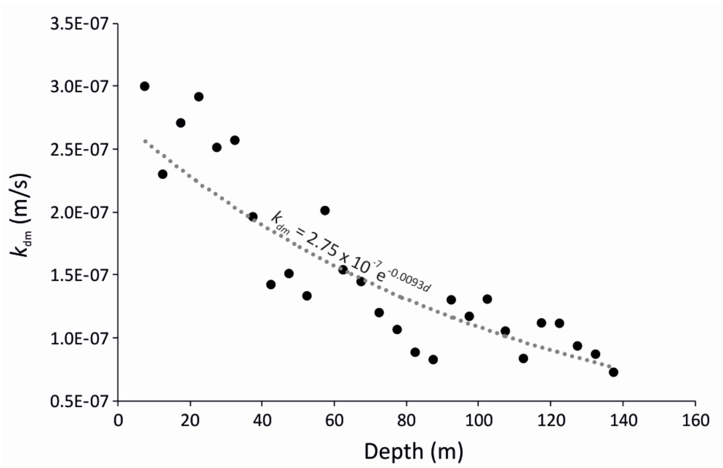

Fig. 6 Plot of k_{dm} (average over 5 m intervals) versus depth

The mean number of discontinuities per meter *f* and *RQD* determined on 5 m intervals of drilling length were also analyzed. The average values of *RQD* and *f*, determined over sections at the same depth, do not show any correlation with depth (Fig. 7). Also the relationships k_d versus *RQD* and k_d versus the mean discontinuity spacing (s_m) are of little significance (Fig. 8).

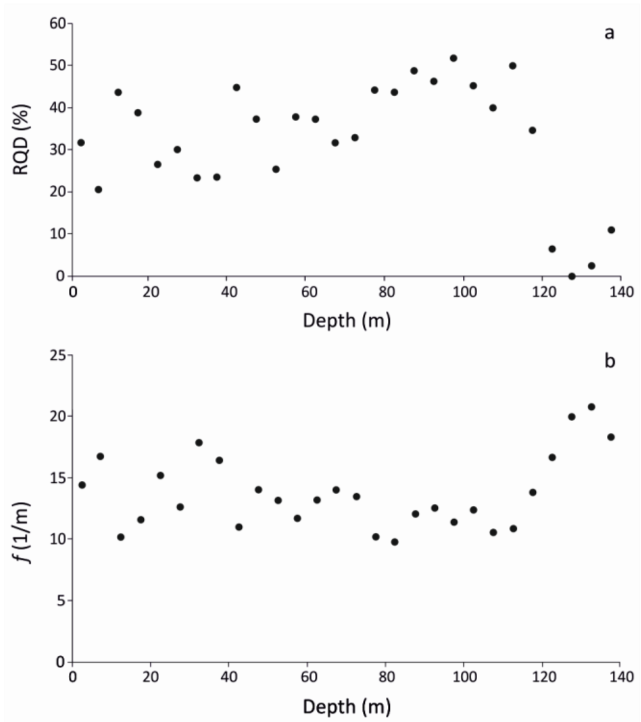

Fig. 7 Plots of *RQD* (**a**) and *f* (**b**) (average value over sections at the same depth) versus depth

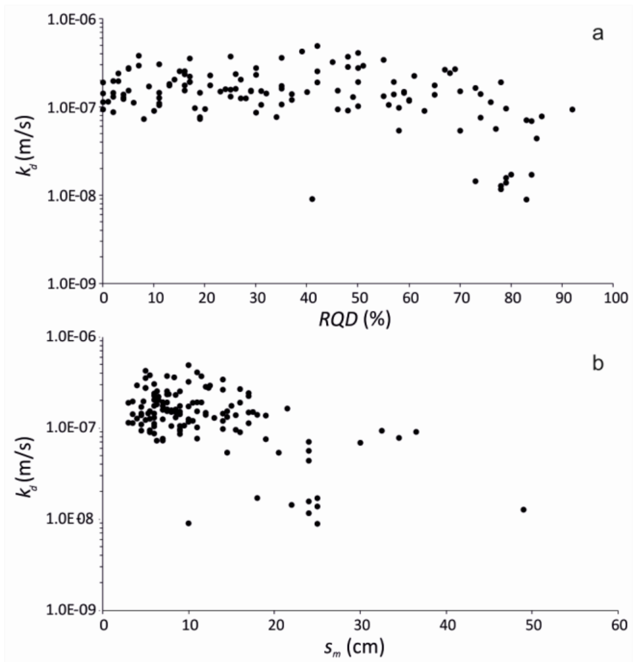

Fig. 8 Plots of k_d versus *RQD* (**a**) and mean discontinuity spacing s_m (**b**)

The 2D resistivity models of the subsurface available for four tested boreholes (BH1-BH4 in Table 1 and Fig. 1) are shown in Figure 9. The resistivity generally varies from 100 to 400 Ωm in the shallow layers (up to about 50 m depth). Then, a general increase in resistivity with depth appears within the depths crossed by drilling, with the exception of the borehole BH4.

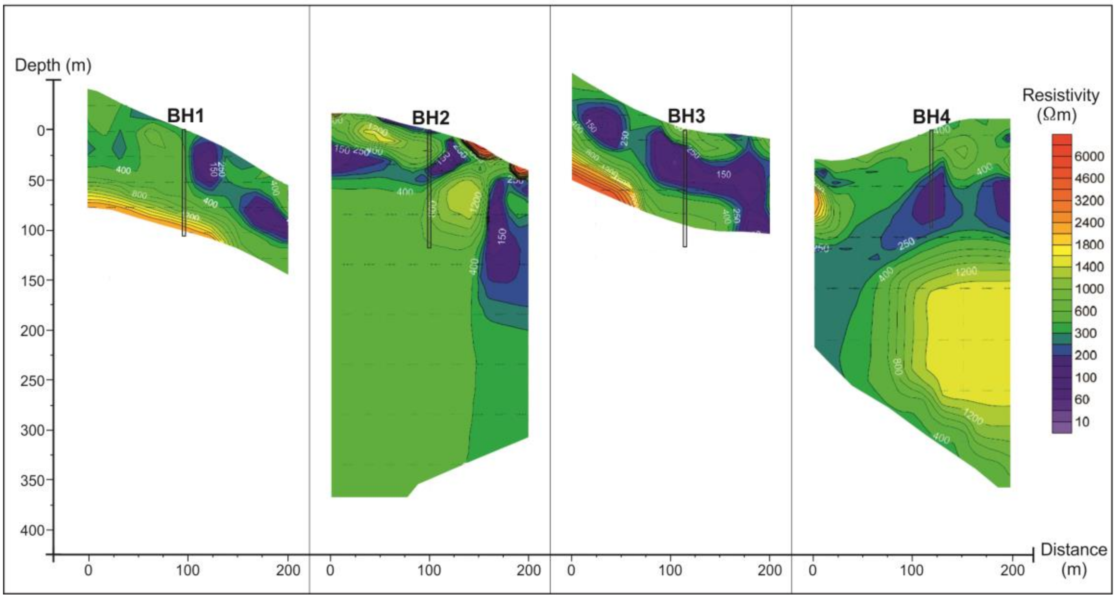

Fig. 9 Inverse model resistivity sections for BH1-BH4 boreholes

4. Discussion

The rocks examined can be considered hard-rocks with low permeability if one refers to the hydraulic conductivity values obtained from injection tests (10^{-8} - 10^{-7} m/s) and the nature of rock formations (mainly andesites and secondly metamorphites).

For hard rocks, the decrease in permeability with depth is reported from several studies and is usually attributed to a reduction in fracture aperture and fracture spacing with depth. Different empirical relationships have been found between permeability and depth. While some equations estimate the hydraulic conductivity simply as a function of depth, others include the hydraulic conductivity close to the surface (e.g., Snow 1968, 1970; Lewis and Burgy 1964; Louis 1974; Carlsson and Olsson 1977; Gale et al. 1982; Lee and Farmer 1993). Although hydraulic data measured in the first hundred meters of depth (and in some cases up to some hundreds of meters) support these empirical relationships, this decrease cannot be taken as a universal behavior. In fact, some studies report significant permeabilities at some thousand meters of depth in fractured rocks (Kessel and Kuck 1995; Stober and Bucher 2005).

In the examined case, a general decrease of rock mass permeability with depth seems to be evident from the results of injection tests, both evaluating single borehole results (Fig. 2 and 5) and combined results (Fig. 6). This is consistent with a general increase of rock mass resistivity with depth highlighted by geophysical prospecting. The empirical relationship obtained from the k_{dm}-d regression can be represented in general terms as follows:

$$k = k_0 e^{-\beta d} \quad (3)$$

where k is the average rock mass permeability (in m/s), k_0 is hydraulic conductivity near ground surface (in m/s) and β is an empirical constant (equal to 9.3×10^{-3} 1/m, in the examined case). This relationship, although obtained from injection tests that are representative of a reduced volume of aquifer, can be used for a preliminary hydraulic characterization of rock mass with relatively uniform lithology and tectonics, as it seems in the case study if one considers the predominance of andesitic rocks crossed by the boreholes and results of the geophysical prospecting (excluding the 2D resistivity section concerning BH4). The equation (3) is site specific; however, the depth dependence of permeability from k_0 makes it comparable with other relationships reported in the literature (e.g., Wei et al. 1995) and in particular with the one found by Louis (1974) (Table 2).

No correlation was found between the number of discontinuities per meter *f* and depth within the investigated depths (up to 140 m), even when the mean value of *f* measured at the same depth interval was considered. Nor even an increase of *RQD* with depth was found. On the other hand, the low value of the mean discontinuity spacing found for all boreholes is consistent with the structural setting of the area, due to the intense tectonic activity that affected the region (Okay 2008).

Given the absence of correlation between discontinuity spacing and depth (Fig. 7), and between hydraulic conductivity and spacing (Fig. 8), it follows that the declining trend of hydraulic conductivity with depth must rely upon other variables. One could think to a decrease of the hydraulic aperture of the discontinuities, as found in other cases in the literature (e.g., Snow 1968, 1969; Bandis et al. 1983, 1985).

The relationship found between rock mass permeability and depth, equation (3), was compared with other equations already known in the literature. Among the several empirical relationships derived from hydraulic tests, the relations proposed by Louis (1974), Carlsson and Olsson (1993) and Wei et al. (1995) reported in Table 2 were considered. In Figure 10 the variation of rock mass permeability is shown according to the different relationships of Table 2, and considering the k_0-values determined for the examined case (3.64×10^{-7} and 0.84×10^{-7} m/s; Fig. 5), when required. The comparison highlights that the k values from equation (3) fall between those determined by Wei et al. (1995) and Louis (1974), which are dependent on k_0. In particular, the equation (3) is a negative exponential relation as those found by Louis (1974), despite the different rocks considered, i.e., crystalline rocks in Louis 1974 and mainly andesite in the present study. The only difference is the value of the multiplicative coefficient of the depth β, which is higher than the Louis coefficient α (Table 2). Comparing the other equations, a wider variation of k with depth appears in Carlsson and Olsson (1993) and Wei et al. (1995).

From a practical point of view, the empirical relation found for the hydraulic conductivity as a function of depth can be used for an initial hydraulic characterization of fractured media, such as precisely the hard rocks. Layers with different relative permeability can be conceptualized, and the approximate depth where groundwater circulation becomes inactive can be estimated, at least in case of certain geologically homogeneous area. The equation (3) is easily applicable in consideration of input data required: a preliminary verification of hydro-structural homogeneity of rock mass through geological survey and geophysical prospecting, and results of hydraulic tests, to characterize surface rock permeability (k_0).

Table 2 Equations between permeability and depth considered for comparison

Equation	Reference	Units of measurement
$k = k_0 e^{-ad}$	Louis 1974	*k* and k_0 in m/s, *d* in m, *a* empirical coefficient between 3.4×10^{-3} and 7.8×10^{-3} 1/m
$k = 10^{-(1.6\ \log d+4)}$	Carlsson and Olsson 1993	*k* in m/s, *d* in m
$k = k_0\left(1 - \dfrac{d}{58.0 + 1.02d}\right)^3$	Wei et al. 1995	*k* and k_0 in m/s, *d* in m
$k\ =\ k_0 e^{-\beta d}$	Present study	*k* and k_0 in m/s, *d* in m, *β* empirical coefficient equal to 9.3×10^{-3} 1/m

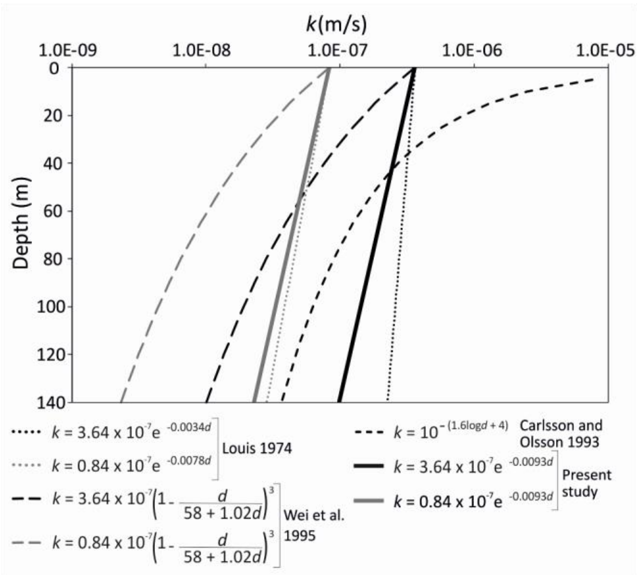

Fig. 10 Comparison of the variation of rock mass permeability determined in the present study with other relationships obtained from the literature

The case study represents a further contribution to the equations already proposed in the literature relying the rock mass permeability with depth, and specifically to those dependent on the surface rock permeability, such as those found by Louis (1974). It also emerges that the applicability of these relationships requires a hydro-structural homogeneity of the rock mass that can be verified through inexpensive geophysical prospecting.

In the examined case, the discontinuity spacing has little influence on the decrease of rock mass permeability with depth. This may be due to the restricted depth of investigation. The observed phenomenon could also indicate a stronger influence over depth dependence of permeability due to the decrease in the average hydraulic aperture, which would be consistent with the assumption of the cubic law (Snow 1968; Witherspoon et al. 1980).

5. Conclusions

Measurements on a total of 660 m of core logging and results of 132 injection tests concerning hard rocks of Western Turkey, framed in a broader context by means of resistivity profiles, allowed the analysis of the relation among permeability of rock mass, discontinuity spacing and depth. The following conclusion were obtained.

- Within the depth of investigation (the first hundred meters), the average hydraulic conductivity of the rock mass shows an exponential declining trend with the depth, and depends on the surface value of the hydraulic parameter.
- There is no correlation between discontinuity spacing and depth, nor between *RQD* and depth.
- The empirical relationship found between permeability of rock mass and depth is consistent with other reported in the literature including the dependence of the permeability with depth on the surface rock permeability, and specifically with those found by Louis (1974).
- The similarity found between the equation of the present study, obtained from investigations conducted in andesitic rocks, and those of Louis (1974), concerning crystalline rocks, broadens the scope of application of these empirical relationships in fractured rock with low permeability, regardless of their nature, but rather considering their specific structural setting.
- The case study also highlights that 2D resistivity profiles can represent a valuable support to verify the hydro-structural homogeneity of rock mass, which allows to define the limits of application of empirical relations. In fact, empirical coefficients in the equation found, as well as in the other relationships, are site-specific.
- The relationships between the rock mass permeability and depth, and specifically those dependent on the surface rock permeability, can be useful in engineering projects when a preliminary vertical characterization of hydraulic conductivity is required. The trend found can be a valuable support in planning the depth of specific investigations or for instance in numerical modelling, where conceptualization of vertical layering in hard rocks is not an easy task.

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Figure 1

Click here to download Figure Fig.1.tif

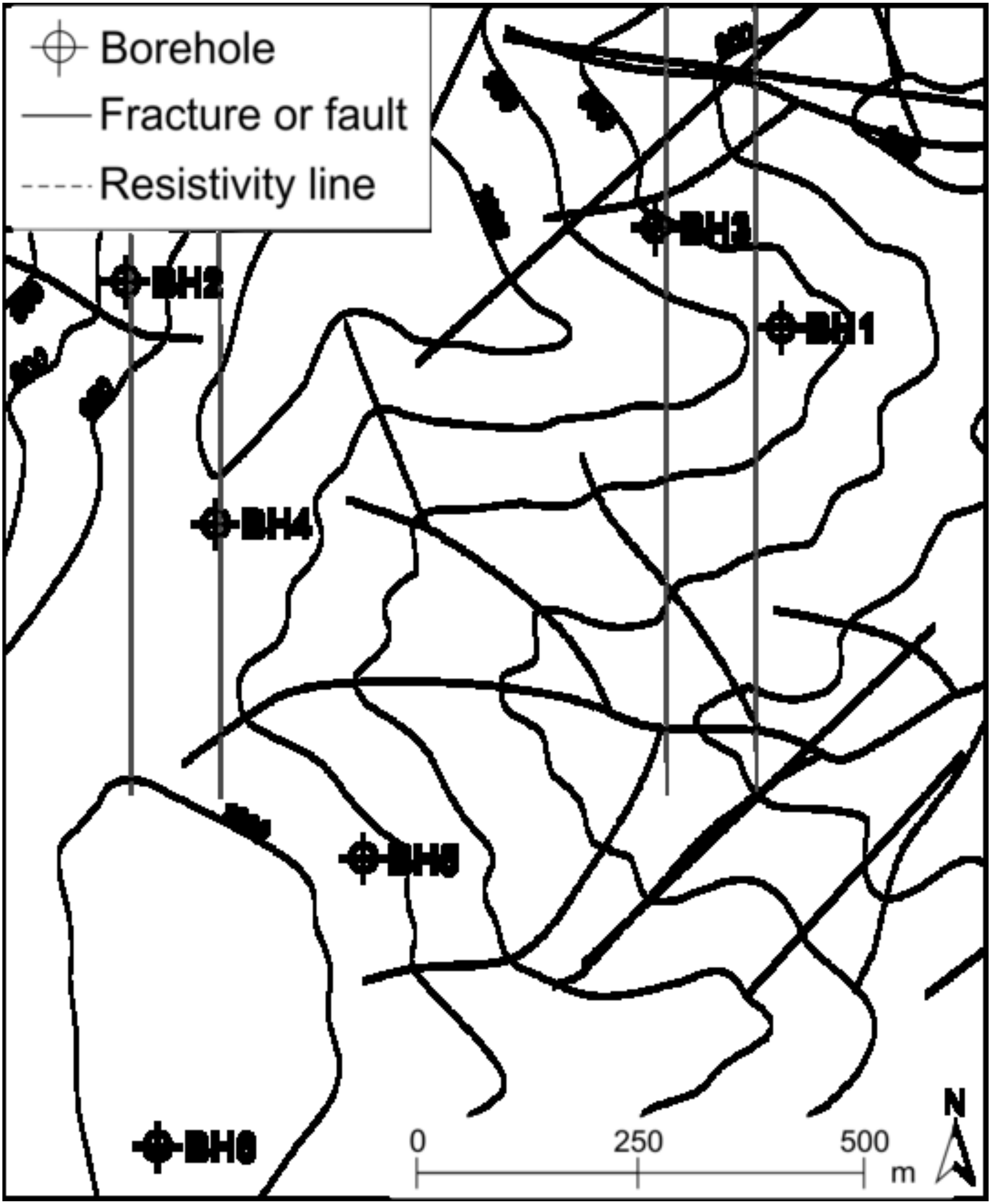

Figure 2

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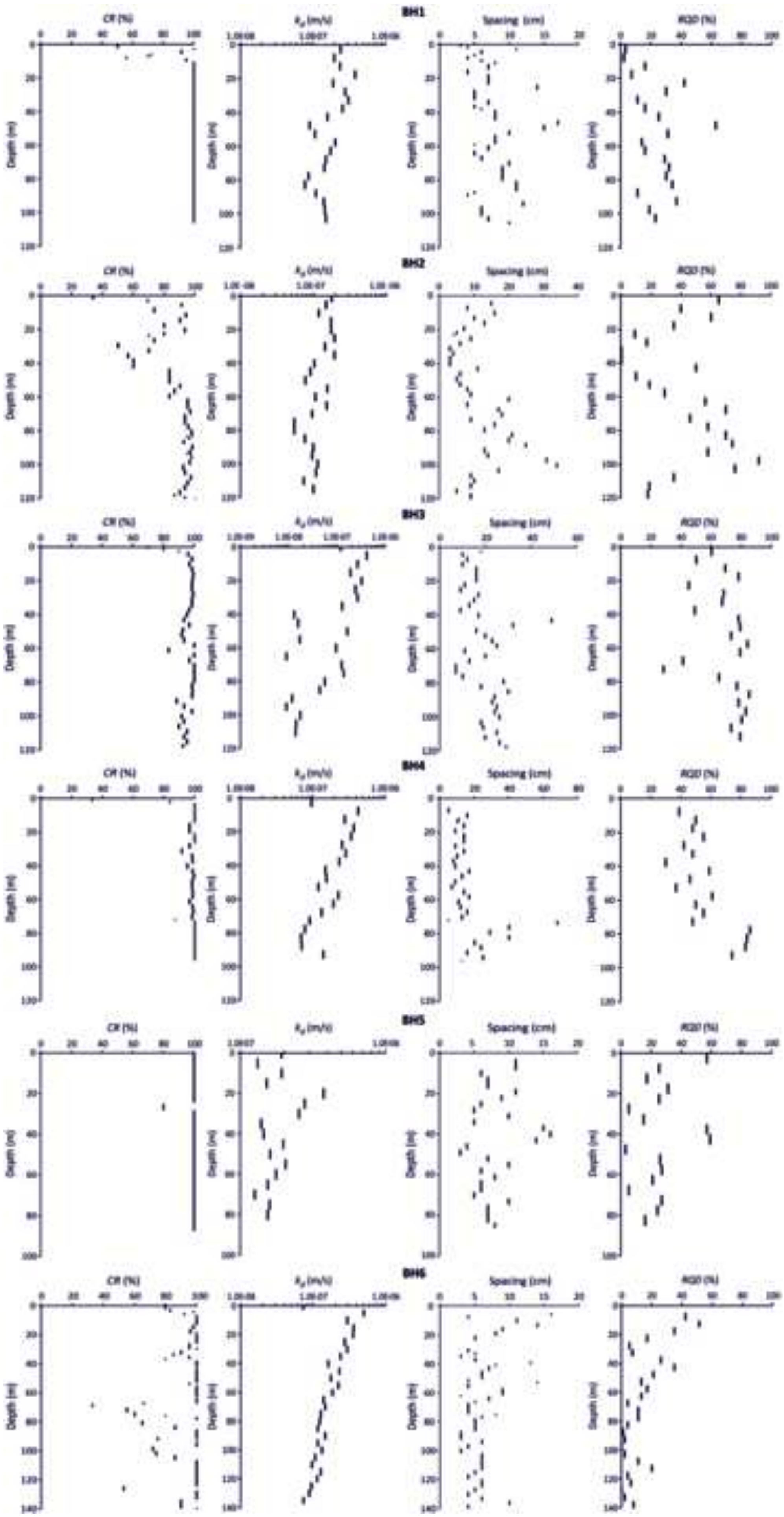
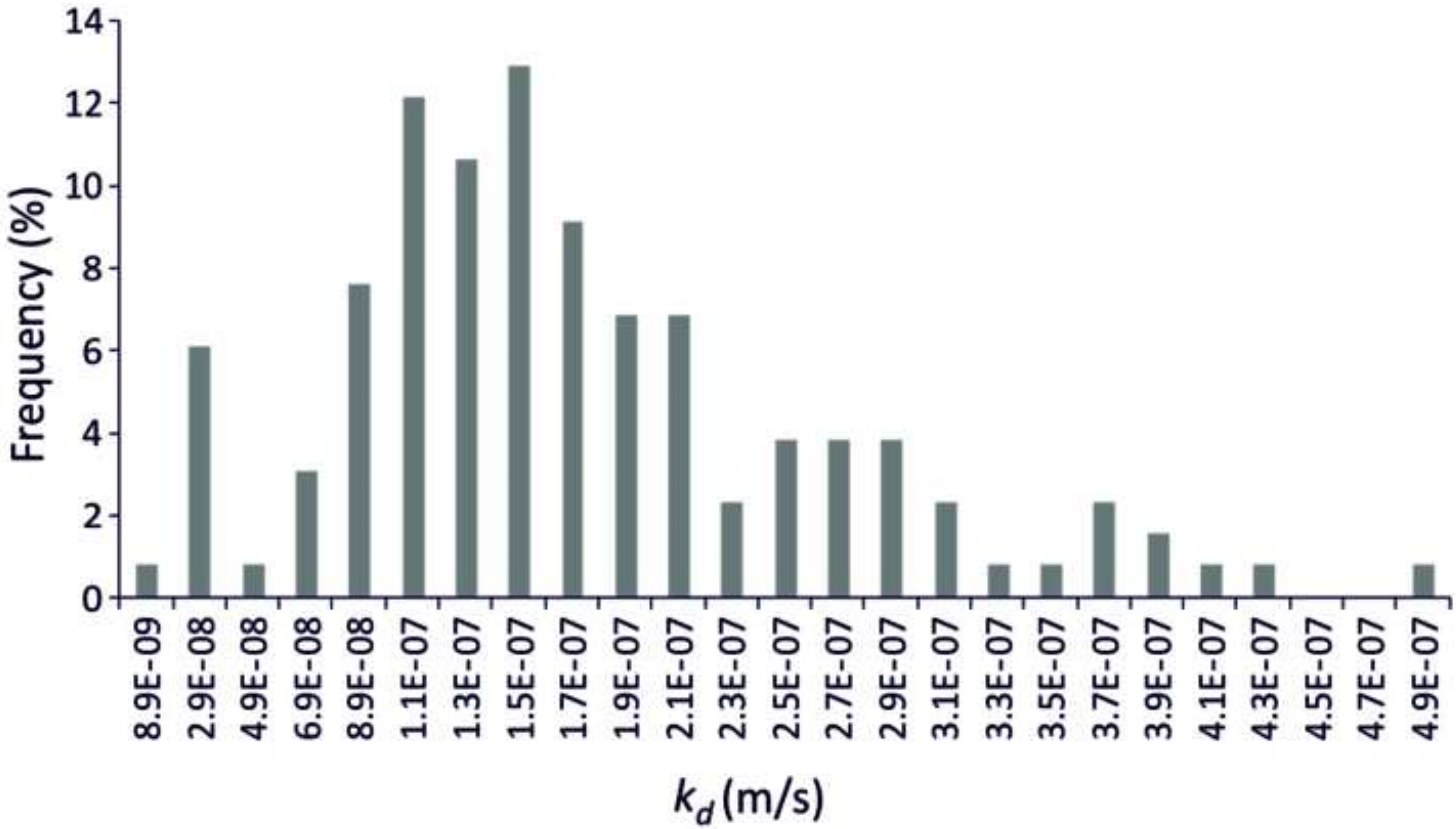


Figure 3 Click here to download Figure Fig.3.tif



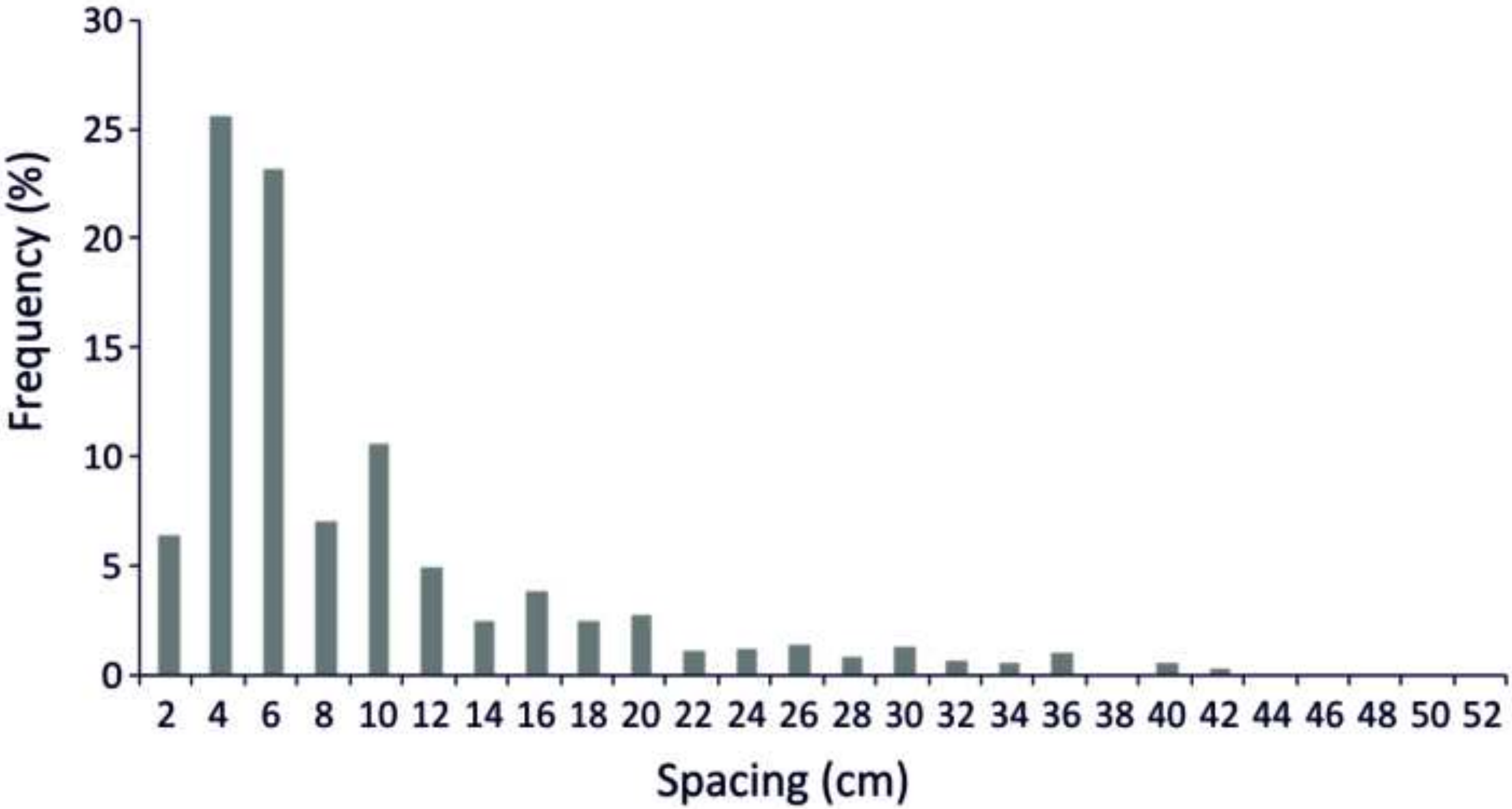

Frequency (%)
30
25
20
15
10
5
0
2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40 42 44 46 48 50 52
Spacing (cm)

Figure 5

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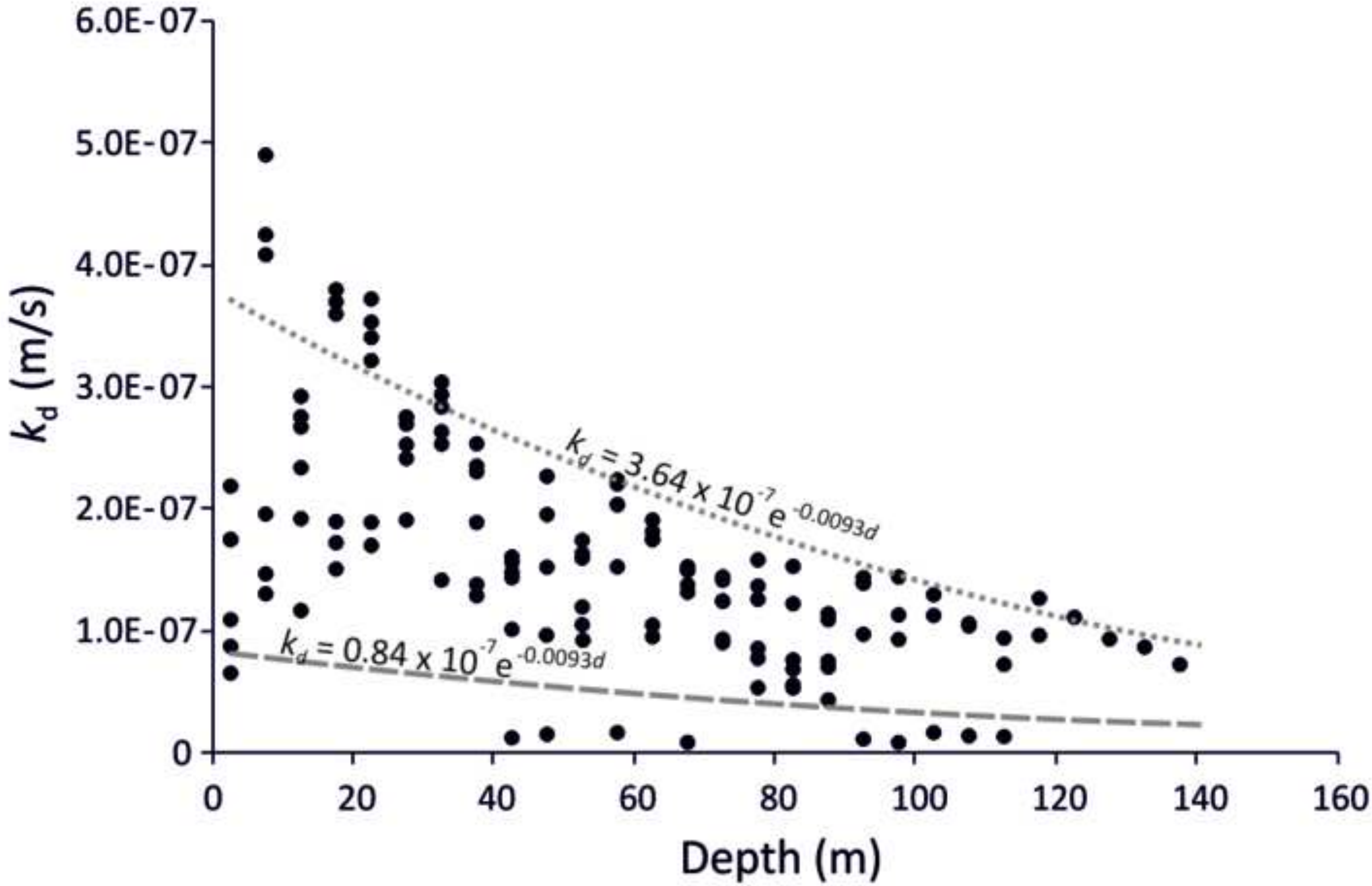

Figure 6

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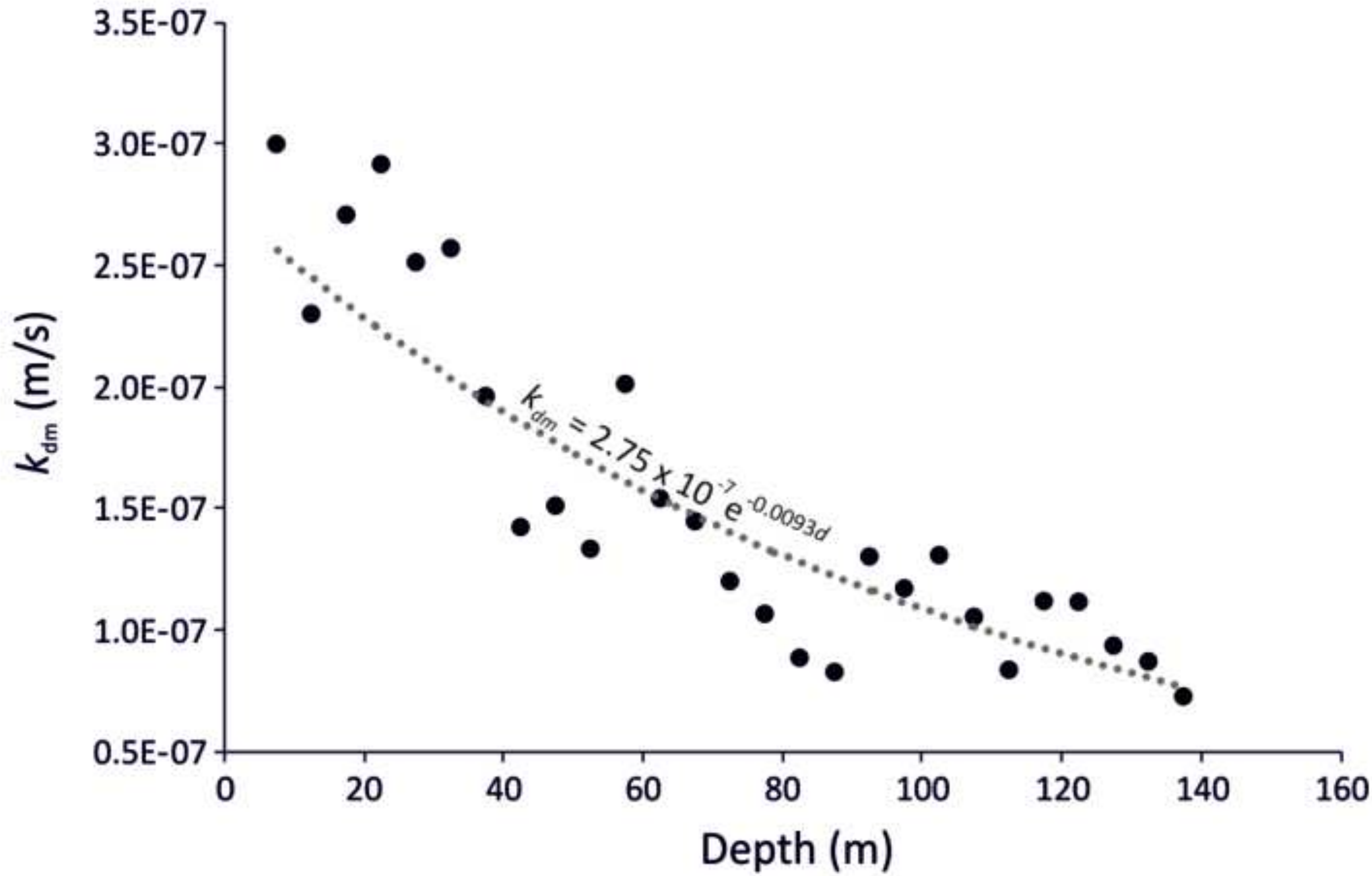

Figure 7

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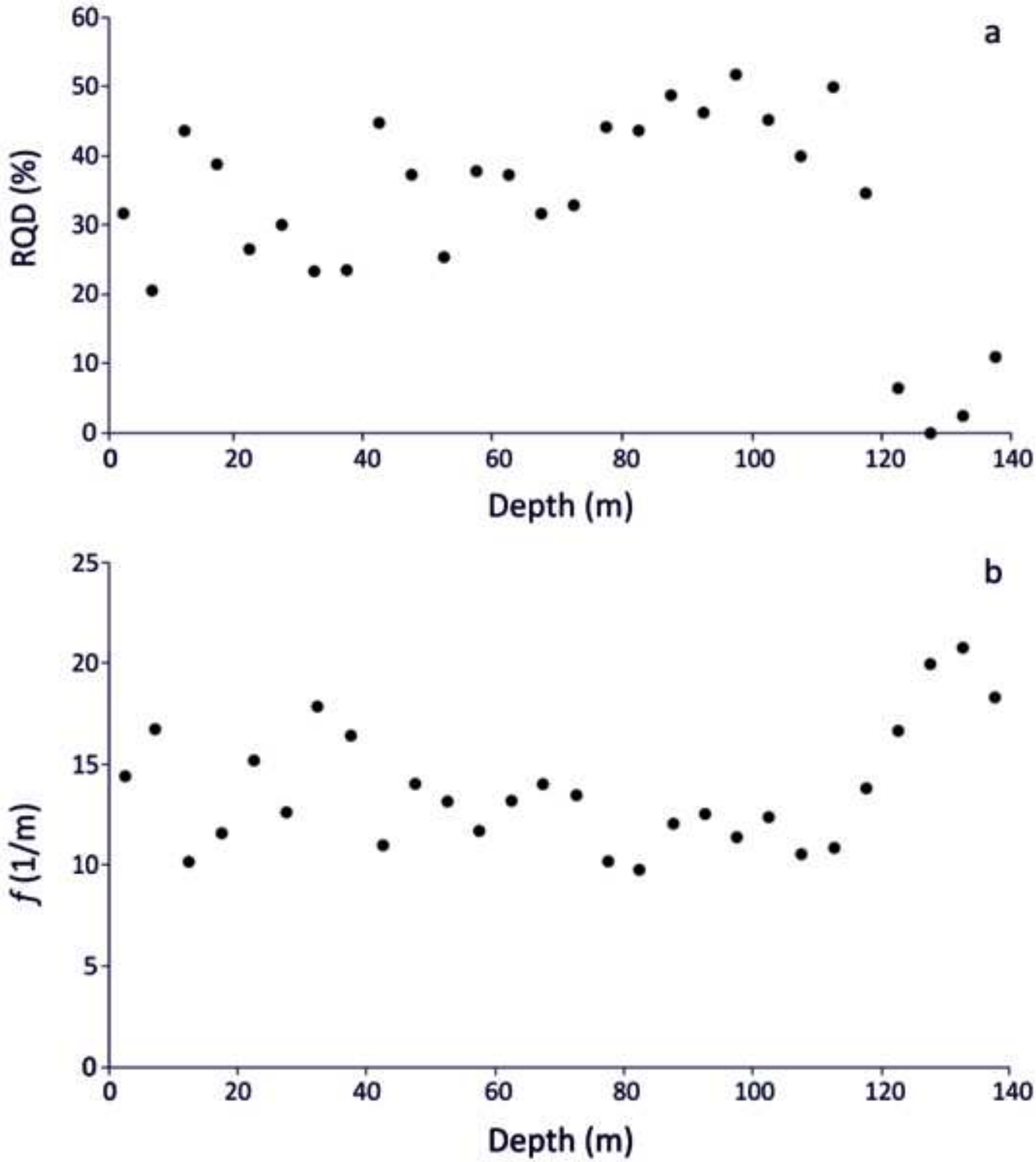


Figure 8

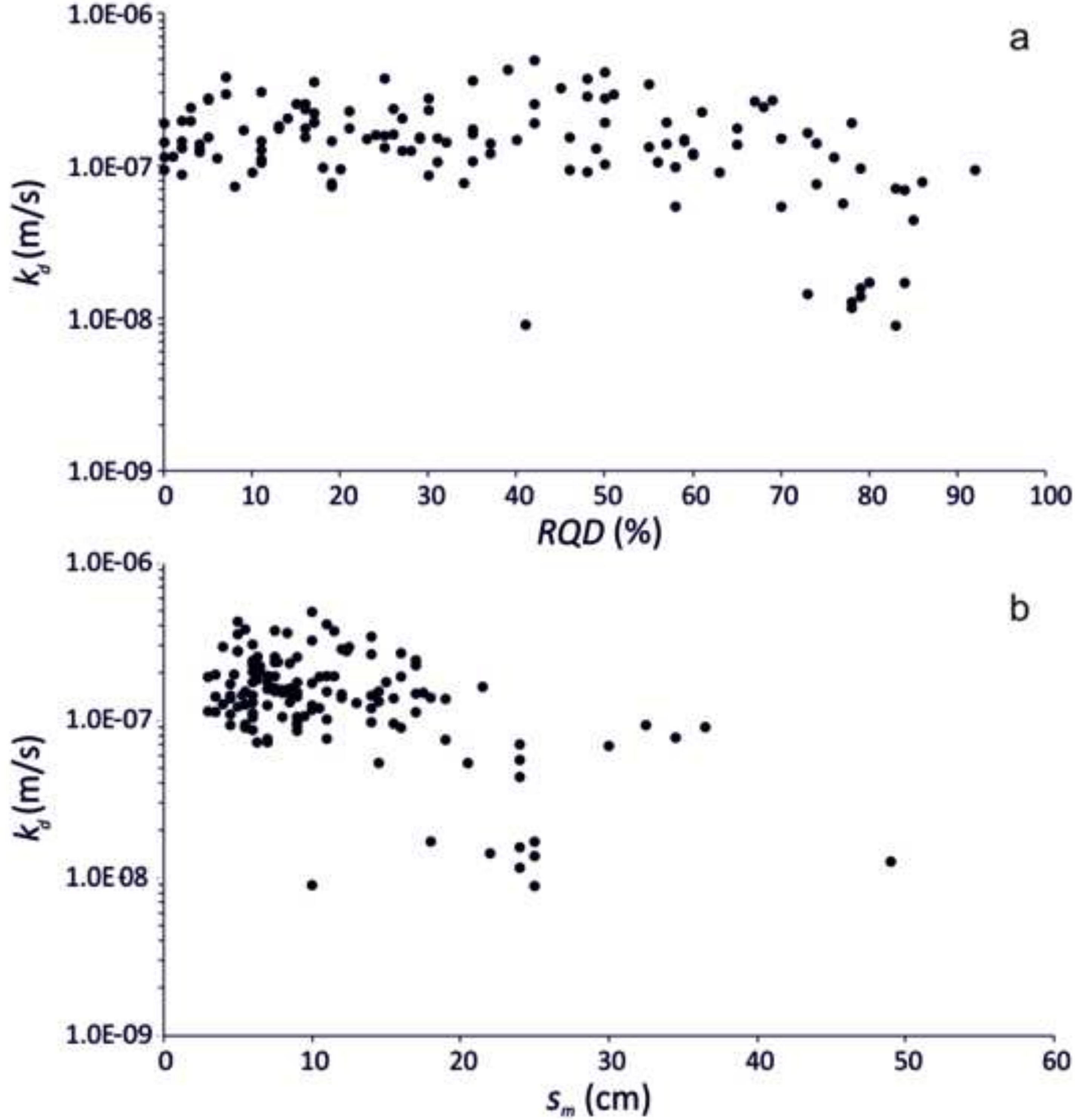

a
1.0E-06
1.0E-07
1.0E-08
1.0E-09
k_d (m/s)
0
10
20
30
40
50
60
70
80
90
100
RQD (%)
b
1.0E-06
1.0E-07
1.0E 08
1.0E-09
k_d (m/s)
0
10
20
30
40
50
60
s_m (cm)

Figure 9

Click here to download Figure Fig.9.tif

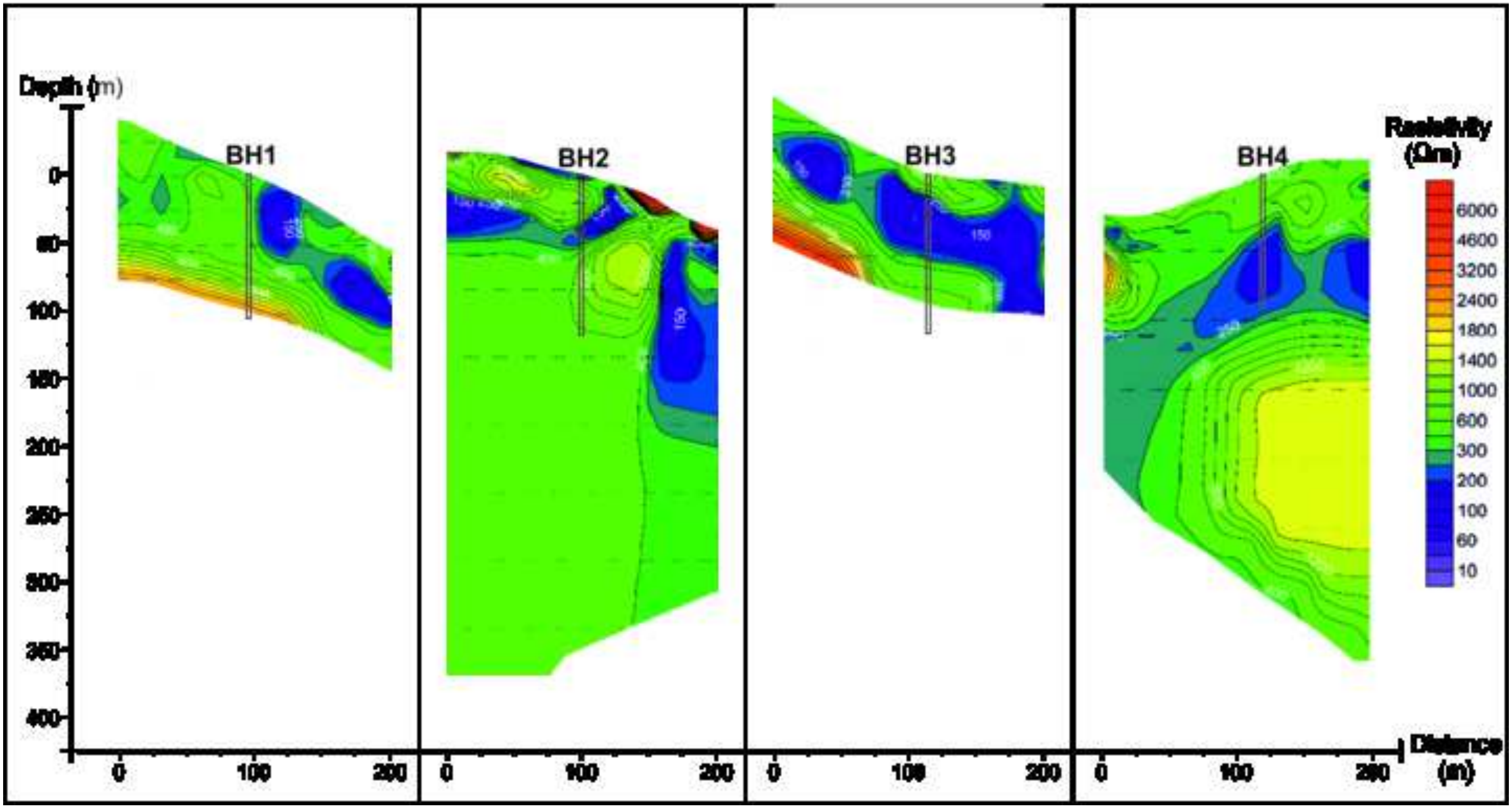
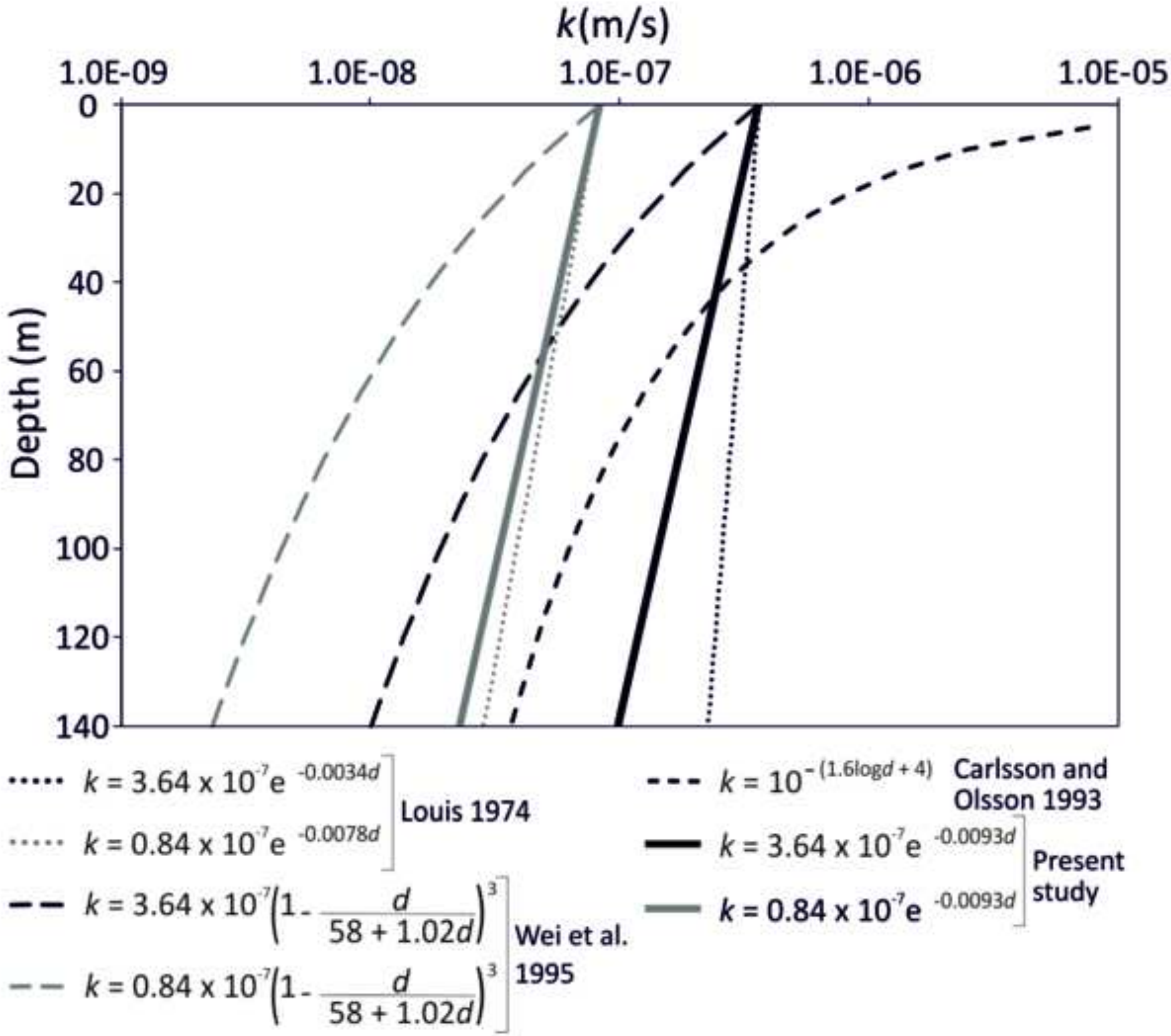


Figure 10


k(m/s)
1.0E-09
1.0E-08
1.0E-07
1.0E-06
1.0E-05
Depth (m)
0
20
40
60
80
100
120
140
k = 3.64 x 10^-7 e^-0.0034d
k = 0.84 x 10^-7 e^-0.0078d
Louis 1974
k = 3.64 x 10^-7 (1 - d/(58 + 1.02d))^3
k = 0.84 x 10^-7 (1 - d/(58 + 1.02d))^3
Wei et al. 1995
k = 10^-(1.6logd + 4)
Carlsson and Olsson 1993
k = 3.64 x 10^-7 e^-0.0093d
k = 0.84 x 10^-7 e^-0.0093d
Present study