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Is the permeability of crystalline rock in the shallow crust related to depth, lithology or tectonic setting?

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ABSTRACT

The permeability of crystalline rocks is generally assumed to decrease with depth due to increasing overburden stress. While experiments have confirmed the dependence of permeability on stress, field measurements of crystalline permeability have not previously yielded an unambiguous and universal relation between permeability and depth in the shallow crust (<2.5 km). Large data sets from Sweden, Germany and Switzerland provide new opportunities to characterize the permeability of crystalline rocks in the shallow crust. Here we compile *in situ* permeability measurements (n = 973) and quantitatively test potential relationships between permeability, depth (0–2.5 km), lithology (intrusive and metamorphic) and tectonic setting (active and inactive). Higher permeabilities are more common at shallow depths (<1 km), but trend analysis does not support a consistently applicable and generalizable relationship between permeability and depth in crystalline rock in the shallow crust. Results suggest lithology has a weak control on permeability–depth relations in the near surface (<0.1 km), regardless of tectonic setting, but may be a more important control at depth. Tectonic setting appears to be a stronger control on permeability–depth relations in the near surface. Permeability values in the tectonically active Molasse basin are scattered with a very weak relationship between permeability and depth. While results indicate that there is no consistently applicable relationship between permeability and depth for crystalline rock in the shallow crust, some specific lithologies and tectonic settings display a statistically significant decrease of permeability with depth, with greater predictive power than a generalized relationship, that could be useful for hydrologic and earth system models.

Key words: crystalline rock, data mining, data synthesis, hydraulic conductivity, permeability

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Geofluids (2015) **15**, 106–119

INTRODUCTION

The relationship between permeability and depth is critical in the study of groundwater in the shallow crust (<2.5 km). It is often assumed or suggested that the permeability of crystalline rock decreases with depth (Snow 1968; Anderson *et al.* 1985; Morrow & Lockner 1997; Ingebritsen & Manning 1999; Shmonov *et al.* 2003; Saar & Manga 2004; Stober & Bucher 2006; Jiang *et al.* 2010; Stober 2011), although several studies identify anomalies and uncertainties in this expected relationship (Brace 1980, 1984; Huenges *et al.* 1997). Where a relationship is accepted, it is often estimated as an exponential/logarithmic relationship fit to highly variable data (Snow 1968; Anderson *et al.* 1985; Wladis *et al.* 1997; Shmonov *et al.* 2003; Saar & Manga 2004). These relationships typically explain only a small percentage of the variation in the data.

In the shallow crust, lithology may be an important control on permeability. A recent compilation of near-surface (<0.1 km) data clearly indicates that regional-scale permeability values are controlled by lithology (classified in the compilation as unconsolidated, sedimentary, crystalline, volcanic or carbonate) (Gleeson *et al.* 2011). Similarly, the permeability of crystalline rock has been shown to depend on whether the lithology is gneissic or granitic in the Black Forest region of Germany (Stober 1996). At depths where contact metamorphism can occur (<5 km), the permeability of metamorphosed rocks is lithology-dependent whereas at depths of regional metamorphism (>5–10 km), permeability is not controlled by lithology (Manning & Ingebritsen 1999).

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Permeability in crystalline rock is predominantly secondary fracture permeability, which is controlled by fracture density, aperture and connectivity (Berkowitz 2002; Neuman 2005; Ingebritsen *et al.* 2006), as well as hydromechanical coupling (Earnest & Boutt 2014) and fracture in-filling (Rutqvist 2014). Fracture density, aperture and connectivity are a function of lithology, deformation history and current tectonic setting. The deformation history of crystalline regions is typically long-lasting and complex with multiple events that can reactivate previous structures. For example, Viola *et al.* (2009) suggest that the crystalline bedrock in Sweden is effectively 'saturated' for fractures such that fracture reactivation is more common than fracture generation (Munier & Talbot 1993). Fracture permeability can also be affected by temperature-dependent fluid–rock interactions and fracture in-filling (Rutqvist 2014) that are a function of the geochemistry, temperature history and fluid flux. A recent study by Earnest & Boutt (2014) suggests that hydromechanical coupling also plays a role in controlling fractured rock permeability in the upper crust, with fracture normal stiffness being more important than shear dilation. Horizontal stresses are typically much greater than vertical stresses at shallow depths, but the ratio of horizontal to vertical stress decreases significantly in the upper 1 km of the crust as overburden stress increases (Brown & Hoek 1978; Maloney *et al.* 2006; Earnest & Boutt 2014). For example, Maloney *et al.* (2006) show that for crystalline rock in the Canadian Shield, the near surface (<300–600 m in their study) is dominated by local horizontal stresses, while stresses at greater depth are smaller and controlled by distant boundary conditions.

Our objective was to quantitatively evaluate the relationship between the permeability of crystalline rock and depth, lithology, and tectonic setting. We compiled a data set of 973 *in situ* permeability measurements in crystalline rock from the surface to depths of 2.5 km, from metamorphic and intrusive lithologies and from three different locations representing inactive and active tectonic settings. We focus on permeability–depth relations in the upper 2.5 km of the crust for two reasons. First, this is the depth of 'traditional data' such as core samples, pumping tests and drill stem tests, rather than inferential data on permeability such as metamorphic fluid fluxes. Second, this depth is crucial for hydrologic research and examining the role of groundwater in earth processes at the earth surface and in the shallow crust. We do not explicitly examine the potential role of topography and climatic conditions as most of our data are derived from low-to-moderate topographic settings with humid climates. We significantly expand and update previous permeability compilations and quantitatively assess trends of permeability with depth, lithology and tectonic setting for the first time.

DATA SOURCES, SYNTHESIS AND ANALYSIS

Crystalline rock permeability has been measured *in situ* at various depths in metamorphic and intrusive lithologies, as well as in active and inactive tectonic settings. Laboratory permeability tests are excluded from this compilation because of the well-described discrepancy between laboratory and field estimates of permeability (Brace 1980). Focusing on *in situ* values allows this study to make conclusions about permeability values in the field rather than in the laboratory. We significantly expand on previous permeability compilations that have presented data only as synthesized ranges (Brace 1980) ($n = 21$, 21 sources) or a combination of synthesized ranges and individual data points: Clauser (1992) ($n = 67$, 48 sources); Ingebritsen & Manning (1999) ($n = 201$, 25 sources); Shmonov *et al.* (2003) ($n = 35$, 4 sources); and Juhlin & Sandstedt (1989) ($n = 18$, 7 sources). Note that we use 'compilation' to describe a collection of permeability values from different sources. In this study, permeability–depth data ($n = 973$) were synthesized from sixteen data sources, primarily from research projects for nuclear waste repositories or geothermal resource exploration in Sweden, Germany and Switzerland, with additional small amounts of data from the United States and Canada (Table 1). Herein, we focus our analysis on data from Sweden, Germany and Switzerland, as this is where the majority of the data are from (94% of total data set). Previous compilations have used specific lithologic categories such as granite and gneiss. A more generalized but consistent lithologic categorization is used herein (intrusive and metamorphic) as some rocks categorized as 'granites' or 'gneiss' are not technically granites or gneiss, respectively.

The Fennoscandian Shield in Sweden, the Black Forest region in Southern Germany and the Molasse basin in Switzerland represent three distinct tectonic settings. The data locations are presented in Fig. 1 along with indicators of current tectonic activity (seismicity) and long-term tectonic history (apatite fission track ages). The Fennoscandian Shield has a low density of seismic events, and fission track data around the sample locations in Sweden show that these rocks have exhumed extremely slowly from depths of 4 to 5 km over more than 250 million years (Hendriks *et al.* 2007). The rocks sampled from the Black Forest region and the basement underlying the Molasse basin are relatively close and consist of similar crystalline lithologies, but are derived from different tectonic settings. The Black Forest developed as the eastern rift shoulder of the Upper Rhine Graben following the onset of rifting in the Eocene (Illies 1972). The Black Forest region has a moderate density of seismic events and has experienced exhumation of 1–2 km since the late Eocene, with vertical motion predominantly taking place in the Miocene (Timar-Geng *et al.* 2006; Meyer *et al.* 2010). The Molasse

Table 1 Summary of data sources.

Reference	*n*	Depth (m)	Reported units	Location	Test method	Lithology	Length of tested intervals (m)
Snow (1968)	25	1.9–89	m^2	Colorado, USA	Injection	Metamorphic	<31
Brace (1980)	14	0–2015	darcys	Manitoba, Canada; Cornwall, England, Nevada, New Mexico, South Carolina, Colorado, Wyoming USA	Various	Metamorphic and intrusive	0–30
Gale *et al.* (1982)	147	51–287	m^2	Stripa Mine, Lindesberg, Sweden	Packer	Intrusive	2
Belanger *et al.* (1989)	76*	238–1610	m s^{-1}	Leuggern, Switzerland	Packer	Metamorphic	1–60, 924
Butler *et al.* (1989)	10	2007–2472	m s^{-1}	Weiach, Switzerland	Packer; slug; pulse; drill stem	Metamorphic	7–39, 416
Juhlin & Sandstedt (1989)	14	310–2240	m^2	Cornwall, England; Siljan, Sweden; Bottstein, Switzerland; Cajon Pass, USA	Various	Metamorphic and intrusive	N/A
Ostrowski & Kloska (1989)	27	405–1480	m s^{-1}	Siblingen, Switzerland	Packer; slug; pulse; drill stem	Intrusive	5–359
McCord & Moe (1990)	40*	299–1240	m s^{-1}	Kaisten, Switzerland	Packer; slug; pulse; drill stem	Metamorphic	7–68
Moe *et al.* (1990)	23*	1510–2000	m s^{-1}	Schafisheim, Switzerland	Packer; slug; pulse; drill stem	Intrusive	9–326
Ahlbom *et al.* (1991)	164*	10–695	m s^{-1}	Båven, Sweden	Packer	Metamorphic	25
Stober (1995)	149	12–661	m s^{-1}	Black Forest, Germany	Open-hole	Intrusive and metamorphic	5–358
Huenges *et al.* (1997)	8	208–2130	m^2	Windischeschenbach, Germany	Drill stem	Metamorphic	30–317
Morrow & Lockner (1997)	15	679–1610	m^2	Illinois, USA	Pulse; injection	Intrusive	76–1470
Walker *et al.* (1997)	125	0–1390	m s^{-1}	Oskarshamn, Sweden	Packer	Intrusive	26–389
Wladis *et al.* (1997)	78*	0–625	m s^{-1}	Gidea, Sweden	Injection	Metamorphic	25
SKB (2008)	58*	0–985	m s^{-1}	Forsmark, Sweden	Packer	Metamorphic	20

*These data sets have a detection limit which establishes an artificial minimum permeability.

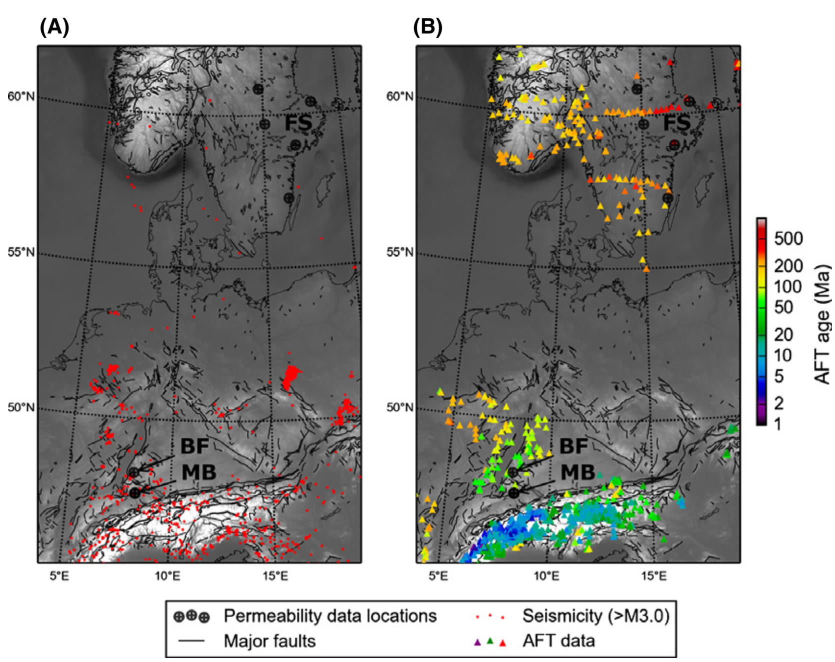

Fig. 1. Locations of permeability data and indicators of (A) short-term (years) and (B) long-term (million years) tectonic activity. Permeability data are derived from Southern Germany and the Black Forest (BF), the Molasse basin (MB) in Switzerland and the Fennoscandian Shield (FS) in Sweden. Seismic events in (A) denote events since the year 2000 that exceed magnitude 3 on the Richter scale from the National Earthquake Information Center (http://earthquake.usgs.gov/regional/neic/). (B) AFT denotes apatite fission track data obtained from Herman *et al.* (2013). Apatite fission track data are a proxy for long-term tectonic activity. The apatite fission track age is approximately equal to the last time the rock outcrop was at a temperature of 120°C (Wagner & Reimer 1972), which at normal geothermal gradients corresponds to a depth of approximately three to five kilometres.

basin has experienced more recent exhumation, with up to 1.2 km of exhumation since the Pliocene (Mazurek *et al.* 2006; Cederbom *et al.* 2011). Sample locations in the Molasse basin are all located within five kilometres of seismic events that exceed magnitude 3 on a Richter scale (Fig. 1). The Black Forest region and the Molasse basin are influenced by similar maximum horizontal stress directions (Hinzen 2003; Reinecker *et al.* 2010). Earthquake fault plane solutions show a normal faulting regime in the Upper Rhine Graben and surrounding areas (Hinzen 2003), while the Molasse basin is currently under a thrust or strike-slip faulting regime (Reinecker *et al.* 2010).

Six different *in situ* permeability measurement methods were used in the synthesized studies: open-hole tests, drill stem tests, packer tests, injection tests, pulse tests and slug tests. Test intervals range from 2 to 1400 m. To be included in the database, data points had to be *in situ* values at depths shallower than 2.5 km. To be included in statistical analysis, data had to be collected from tested intervals smaller than 500 m. The values of hydrogeological parameters are known to change with the scale of observation (Neuman 1994); this 500-m limit reduces the potential for permeability values in the database to be grossly affected by the scale of measurement. An earnest effort was made to include information regarding fracture and fault zone control on permeability in the synthesis. Unfortunately, this information was rarely provided in our compiled data sources and thus could not be included in our analysis. An important assumption in our analysis is that the *in situ* tests represent the permeability over the reported depths. In reality, testing is often controlled by more permeable features such as fractures or fault zones. However, we exclude the potential impact of specific fractures or fault zones as we do not have data on their location, size and hydraulic importance, while also acknowledging the importance of permeable features and the inherent difficulties in determining representative elementary volumes for hydraulic tests (Stober & Bucher 2014). The results of the data synthesis are presented in Fig. 2, and summaries of the sixteen data sources are provided in Table 1. Note in Table 1 that studies in Switzerland and Sweden provide site-specific permeability for one distinct location each, while data from the Black Forest in Germany are a regional synthesis wherein each permeability value represents a different location.

All data were converted to permeability values (m^2) where necessary to ensure consistency in the data set. Permeability (k) data measured in darcys were converted to m^2 through a unit conversion (1 darcy = 9.87×10^{-13} m^2). Converting hydraulic conductivity (K) data measured in m s^{-1} is more complex, requiring values of fluid viscosity and density at depth. We estimate values of viscosity and density by gathering location-specific salinity and temperature data and

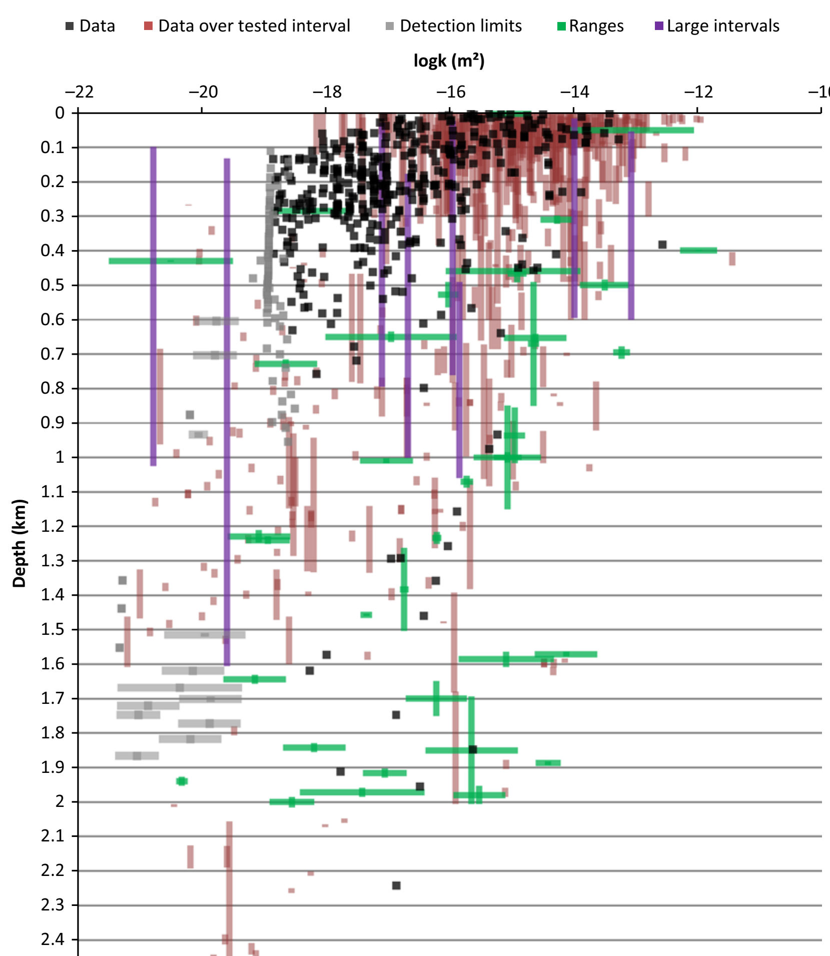

Fig. 2. Full data set of permeability data for crystalline rock (*n* = 973). Black points are singular or average permeability values (*n* = 422). Red lines are permeability values reported over a tested interval (*n* = 426). Grey points are data with reported detection limits (*n* = 80). Green points are the mid-point of permeability values reported as ranges, with the error bar showing the range (*n* = 37). Purple lines are data with tested intervals >500 m (*n* = 8). The vertical extent of a point indicates the extent of the tested interval.

employing known viscosity and density functions dependent on total dissolved solids (TDS) and temperature. Due to the nonlinear relationship of salinity with depth, depth- and location-specific salinity values are determined through linear interpolation of known salinity–depth values from literature. Point-specific temperatures are determined using location-specific geothermal gradients. Summaries of the salinity ranges, temperature functions and data sources for each reference that measured conductivity in m s^{-1} are provided in Table 2. Stuyfzand (1989) specifies the change in density with changes in salinity and temperature as follows:

$$\rho(T, TDS) = 1000 + 805(TDS) - 6.5 \times 10^{-3}(T - 4 + 220(TDS))^2$$

where ρ represents density in kg m^{-3}, T represents temperature in °C and TDS represents salinity in kg kg^{-1}. Batzle & Wang (1992) specify the change in viscosity with changes in salinity and temperature as follows:

$$\mu(T, TDS) = (0.1 + 0.333(TDS) + (1.65 + 91.9(TDS)^3) \times \exp(-a))$$

$$a = (0.42((TDS)^{0.8} - 0.17)^2 + 0.045) \times T^{0.8}$$

where μ represents viscosity in centipoises (this value is converted to Pa-s by dividing by 10^4). After viscosity and density have been estimated, permeability values are calculated from conductivity values as follows:

$$k = K\left(\frac{\mu}{\rho g}\right)$$

where k represents permeability in m^2, K represents hydraulic conductivity in m s^{-1} and g represents the gravitational constant 9.81 m s^{-2}.

Logarithmic functions are fit to the data using simple linear regression. Logarithmic functions are used due to their prevalence as a fitting function in literature (Snow 1968; Anderson *et al.* 1985; Stober 1995; Wladis *et al.* 1997; Ingebritsen & Manning 1999; Shmonov *et al.* 2003; Saar & Manga 2004; Stober & Bucher 2006). Note that the use of a logarithmic function implies an assumption of a lower limit on permeability due to the asymptotic nature of logarithmic functions. Permeability values reported as a range are included in the regression by selecting the mid-point of the range. Permeability values that are reported as a methodological cut-off (n = 80 points of the total data set), which are herein referred to as 'detection limits', are not included in the regressions. We note that excluding detection-limit data may impact the statistical analysis by eliminating a number of low permeability data from the regressions. However, we choose to exclude these values as they are objectively lower quality data that do not describe an actual permeability value. We tested the

Table 2 Summary of salinity and temperature values.

Reference	Location	Salinity range (kg kg^{-1})	Temperature gradient	Salinity source	Temperature source	Salinity source location	Temperature source location
Ahlbom *et al.* (1991)	Båven, Sweden	4.6E-5 to 5.2E-4	5.25°C +12°C per km	Ahlbom *et al.* (1991)	SKB (2008)	Båven, Sweden	Forsmark, Sweden
Walker *et al.* (1997)	Oskarshamn, Sweden	0 to 7.4E-2	5.25°C +12°C per km	Walker *et al.* (1997)	SKB (2008)	Oskarshamn, Sweden	Forsmark, Sweden
Wladis *et al.* (1997)	Gidea, Sweden	1.3E-4 to 5.0E-4	5.25°C +12°C per km	Ahlbom *et al.* (1991) & Gale *et al.* (1982)	SKB (2008)	Båven & Lindesberg, Sweden	Forsmark, Sweden
SKB (2008)	Forsmark, Sweden	9.9E-5 to 1.4E-2	5.25°C +12°C per km	SKB (2008)	SKB (2008)	Forsmark, Sweden	Forsmark, Sweden
Belanger *et al.* (1989)	Leuggern, Switzerland	8.1E-4 to 4.8E-3	11.3°C + 32.9°C per km	Wittwer (1986)	Wittwer (1986)	Leuggern, Switzerland	Leuggern, Switzerland
Butler *et al.* (1989)	Weiach, Switzerland	9E-3 to 3.1E-2	7.8°C + 46.8°C per km	Wittwer (1986)	Butler *et al.* (1989)	Weiach, Switzerland	Weiach, Switzerland
Ostrowski & Kloska (1989)	Siblingen, Switzerland	8.8E-4 to 8.9E-2	9.2°C + 41.1°C per km	Wittwer (1986)	Wittwer (1986)	Siblingen, Switzerland	Siblingen, Switzerland
McCord & Moe (1990)	Kaisten, Switerland	1.2E-3 to 1.3E-3	11.2°C + 36.6°C per km	Wittwer (1986)	Wittwer (1986)	Kaisten, Switerland	Kaisten, Switerland
Moe *et al.* (1990)	Schafisheim, Switzerland	8E-3 to 1.4E-2	5.4°C + 39.3°C per km	Wittwer (1986)	Moe *et al.* (1990)	Schafisheim, Switzerland	Schafisheim, Switzerland
Stober (1995)	Black Forest, Germany	1.2E-4 to 7.4E-3	11.2°C + 33.2°C per km	Stober (1995)	Stober (1995)	Black Forest, Germany	Black Forest, Germany

importance of excluding these cut-off values by artificially assigning them a permeability value one and two orders of magnitude lower than their reported values, and found that this did not significantly change any of the statistical results. The R^2 value of the regression is used to quantify the quality of the derived fit. A *t*-test on the slope parameter was performed for each regression. The *t*-test evaluates the discrepancy between the derived slope and a slope of zero, indicating no relationship, and requires an assumption of normality in the regression error. Passing the *t*-test implies that there is a statistically significant relationship of permeability with depth; low R^2 values imply that the derived function is a poor predictor of permeability with depth.

The importance of different variables (depth, lithology and tectonic setting) was examined by dividing the permeability data into different categories and comparing these categories using the nonparametric Kolmogorov–Smirnov (KS) test (Lilliefors 1967). The KS test is a statistical method that identifies whether two distributions are derived from the same distribution. Failing the KS test indicates that the two distributions are not similar enough to be derived from the same distribution. We use the KS test to quantify the difference between permeability distributions at different depth intervals, as well as to test relationships between lithologies (intrusive or metamorphic) and tectonic setting (Fennoscandian Shield, Southern Germany, and Molasse basin).

RESULTS AND DISCUSSION

In Fig. 2, data points with tested intervals greater than 500 m ($n = 8$) and data points representing detection limits ($n = 80$) are presented for context, but excluded from the following statistical analyses. A summary of the regression analyses and Kolmogorov–Smirnov tests are provided in Tables 3 and 4, respectively.

Table 3 Summary of regression analyses.

Data Set	*t*-test *P*-value	R^2	*n*
All	1.32E-09	2.30E-01	885
Intrusive	2.49E-03	1.29E-01	390
Metamorphic	1.99E-07	3.00E-01	495
Southern Germany	3.91E-03	3.91E-01	152
Southern Germany metamorphic	5.05E-04	5.43E-01	107
Southern Germany intrusive	**9.46E-01**	**4.98E-03**	**45**
Fennoscandian Shield	1.25E-02	1.53E-01	515
Fennoscandian Shield metamorphic	**1.54E-01**	**1.91E-01**	**236**
Fennoscandian Shield intrusive	**1.03E-01**	**9.11E-02**	**279**
Molasse basin	3.82E-03	5.21E-02	159
Molasse basin metamorphic	1.33E-03	8.80E-02	119
Molasse basin intrusive	1.78E-02	1.26E-01	40

Bold indicates data sets which show no statistically significant decrease of permeability with depth at 5% significance.

All data

The average permeability of the entire data set excluding tested intervals >0.5 km and detection limits (Fig. 3, $n = 885$) is -16.3 ± 1.81 m^2 ($\mu_{logk} \pm \sigma_{logk}$, where μ_{logk} is the arithmetic mean and σ_{logk} is the standard deviation. Note that all reported 'averages' refer to the arithmetic mean). The frequency of permeability data decreases with depth (Fig. 4). Although an ideal statistical analysis would have data randomly distributed over the 2.5-km range examined in this analysis, the realities of *in situ* data acquisition create a shallow data bias in the synthesized data set.

A statistically significant logarithmic fit exists through the data at <1% significance ($P = 1.32e{-9}$), although this function has a low predictive power ($R^2 = 0.230$). The logarithmic fit shows minimal qualitative agreement with both the Shmonov *et al.* (2003) fit and the Manning–Ingebritsen fit (Ingebritsen & Manning 1999) in the entire 2.5-km range. The lack of agreement with the Manning–Ingebritsen fit is not unexpected, as this fit was derived to describe much deeper permeability data than examined in this analysis. Although the data support the assumption of a decrease of permeability with depth, the low predictive power of the derived logarithmic fit illustrates the ineffectiveness of a general logarithmic permeability–depth relationship as a tool to predict permeability values. Stober & Bucher (2006) also reached this conclusion in the analysis of a smaller crystalline rock data set.

Multiple KS tests were performed to determine an appropriate cut-off between 'deeper' and 'near-surface' data (Table 4). KS tests examining cut-offs from 0.1 to 1.0 km display *P*-values at least two orders of magnitude below the 5% significance cut-off in all cases, indicating that *P*-values are not useful for assigning a depth cut-off. Therefore, we use the arbitrary depth cut-off of 0.1 km which (i) maintains a reasonable statistical size above and below the cut-off, (ii) is consistent with previous near-surface permeability compilations (Gleeson *et al.* 2011), and (iii) allows calculation of permeability values which could be useful for near-surface hydrologic modelling. Hereafter, 'near-surface' permeability refers to <0.1 km depth and 'deeper' permeability refers to >0.1 km depth. The average permeability in the near-surface data is -15.0 ± 1.36 m^2 ($n = 265$), approximately two orders of magnitude higher than the average permeability in the deep data (-16.8 ± 1.71 m^2, $n = 620$). Higher permeabilities at shallow depths could be due to larger fracture apertures, greater connectivity or higher fracture density due to low overburden stress, unloading following glacial isostatic rebound and/or the development of sheeting fractures. Rutqvist (2014) describes how large stresses can create highly conducive 'locked-open' fractures that do

Table 4 Summary of Kolmogorov–Smirnov tests.

Data Set a	Data Set b	n_a	n_b	P-value
All < 0.1 km	All > 0.1 km	265	620	1.66E-31
All < 0.2 km	All > 0.2 km	425	460	1.60E-22
All < 0.3 km	All > 0.3 km	557	328	3.07E-15
All < 0.4 km	All > 0.4 km	622	263	3.00e-15
All < 0.5 km	All > 0.5 km	676	209	1.17E-14
All < 0.6 km	All > 0.6 km	698	187	2.44E-14
All < 0.7 km	All > 0.7 km	719	166	2.15E-15
All < 0.8 km	All > 0.8 km	735	150	5.82E-13
All < 0.9 km	All > 0.9 km	757	128	1.08E-14
All < 1.0 km	All > 1.0 km	776	109	3.24E-13
Intrusive < 0.1 km	**Metamorphic < 0.1 km**	**137**	**128**	**4.83E-01**
Intrusive > 0.1 km	Metamorphic > 0.1 km	253	367	4.20E-08
Fennoscandian < 0.1 km	S. Germany < 0.1 km	156	81	1.20E-10
Fennoscandian > 0.1 km	S. Germany > 0.1 km	359	71	3.00E-13
Fennoscandian intrusive < 0.1 km	S. Germany intrusive < 0.1 km	106	29	2.32E-05
Fennoscandian metamorphic < 0.1 km	S. Germany metamorphic < 0.1 km	50	52	2.49E-04
Fennoscandian intrusive < 0.1 km	**Fennoscandian metamorphic < 0.1 km**	**106**	**50**	**7.59E-01**
S. Germany intrusive < 0.1 km	S. Germany metamorphic < 0.1 km	29	52	4.93E-02
Fennoscandian intrusive 0.4–2 km	**Molasse intrusive 0.4–2 km**	**25**	**40**	**1.23E-01**
Fennoscandian 0.4–2 km	Molasse 0.4–2 km	72	140	1.58E-04
Fennoscandian > 0.3 km	Molasse > 0.3 km	129	155	8.79E-07

Bold indicates data sets which show statistical similarity at 5% significance.

not close in response to large overburden stresses, potentially introducing large permeability values at depth. Rutqvist (2014) also notes that mineral precipitation and dissolution may play a role in creating 'locked-open' fractures. Earnest & Boutt (2014) describe an even more explicit relationship between permeability and stress in fractured rock, describing how stress magnitude, shear stiffness and normal stiffness are dominant controls on fracture aperture, and thus permeability, in the upper 1 km of the subsurface.

Lithology

Both intrusive and metamorphic lithologies display a statistically significant logarithmic decrease of permeability with depth, although again with a low predictive power (Fig. 5, Table 3). The average permeability of the intrusive data set is almost one order of magnitude larger than the metamorphic average (intrusive = -15.9 ± 1.69 m^2; metamorphic = -16.6 m^2 $\pm$ 1.83 m^2) although this difference is within one standard deviation. The metamorphic data display a fit with more predictive power than the all-data case, although the R^2 value is still low ($R^2 = 0.300$). A KS test on data in the near surface (<0.1 km) in each lithology shows that intrusive and metamorphic data are statistically similar at 5% significance ($P = 0.483$), indicating that lithology may be a weak control on crystalline rock permeability in the near surface. A KS test on deeper data shows that intrusive and metamorphic data are statistically dissimilar at 5% significance ($P = 7.41 \times 10^{-3}$). The histograms for metamorphic data in the four arbitrary depth intervals in Fig. 5 display a smoother transition to low permeability values with depth (a steady decrease in permeability) as compared to the intrusive data, which display a much more discontinuous transition towards deeper depth intervals. Both data sets include large values of permeability at depth (e.g. 10^{-14} m^2 values below 1.5 km), although large permeability values are less frequent in the metamorphic data.

This analysis suggests that lithology (classified broadly as either 'metamorphic' or 'intrusive') might not be a critical control on crystalline rock permeability at near-surface depths. Metamorphic data display better agreement with a logarithmically declining permeability–depth function as compared to intrusive data. Intrusive rocks display a higher average permeability than metamorphic rocks over the entire 2.5-km-depth range (Fig. 5). Both intrusive and metamorphic data sets show a statistically significant logarithmic decrease in permeability with depth. This conclusion agrees with Stober (1996) who found that granitic rocks had higher conductivities than gneissic rocks and that gneissic rocks display a decrease in permeability with depth. Note however that in the Stober (1996) analysis, granitic rocks display no decrease with depth, which is not the case with the intrusive data in this analysis.

Tectonic setting

Each tectonic setting displays a statistically significant logarithmic decrease of permeability with depth, although with low predictive power (Fig. 6). The fit derived from the Southern Germany data displays the highest predictive power ($R^2 = 0.391$), while the fit from the Molasse basin displays almost no predictive power ($R^2 = 0.052$), although the lack of near-surface data in the Molasse basin

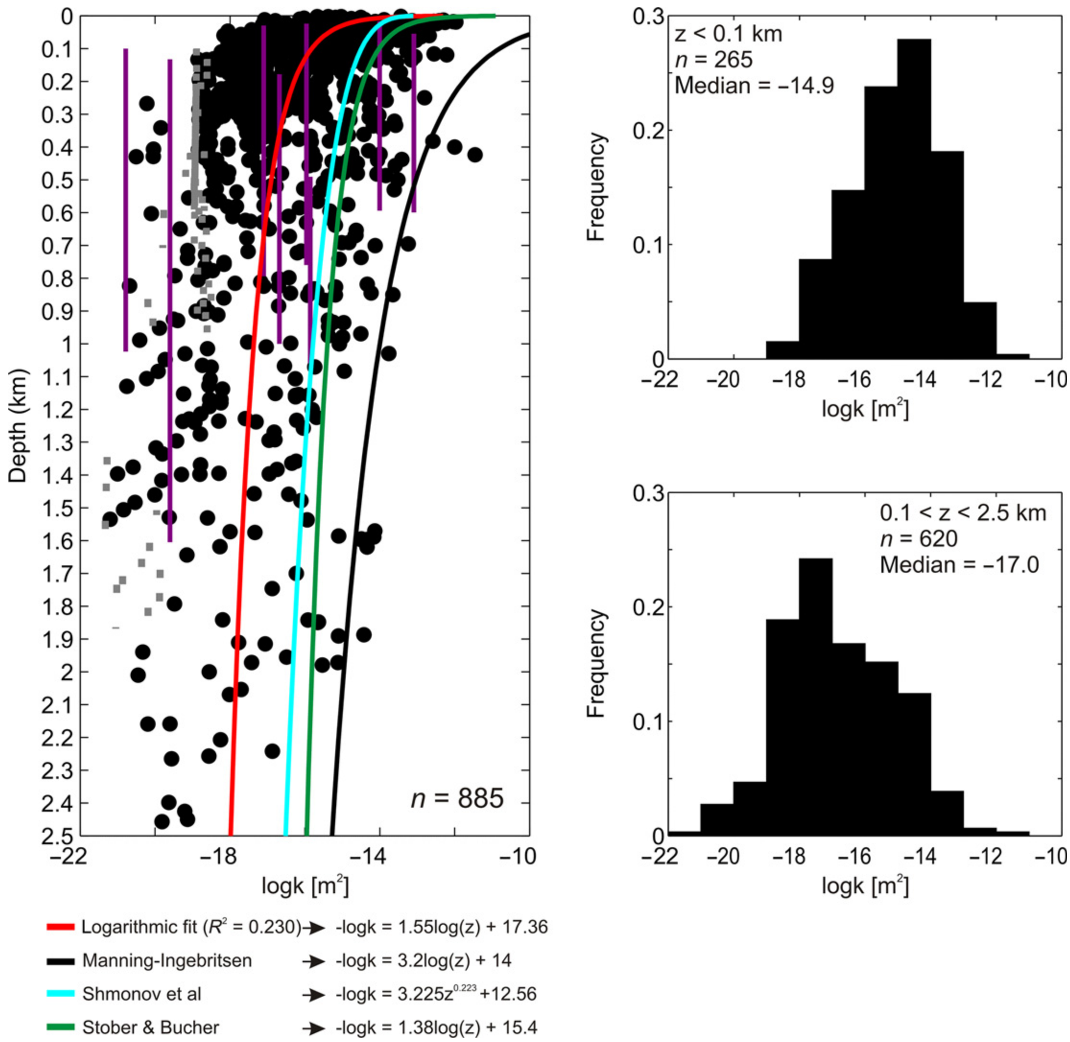

Fig. 3. The relationship between permeability and depth for the full data set, with error bars removed for clarity. Ranges plotted as the mid-point. Grey rectangles indicate measurements at a detection limit. Purple lines indicate data points from tested intervals greater than 500 m. Red line indicates logarithmic fit through data (R^2 = 0.230). Black line indicates Manning–Ingebritsen fit (Ingebritsen & Manning 1999). Blue line indicates Shmonov *et al.* (2003) fit. Green line indicates Stober & Bucher (2006) fit. Histograms display distribution of permeability data above and below 0.1 km.

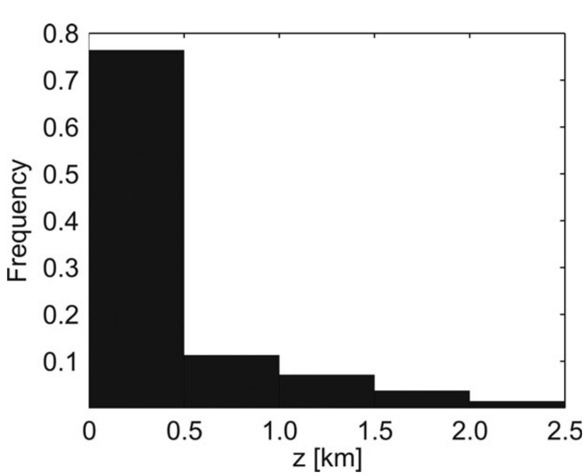

Fig. 4. The distribution of permeability values in the full data set.

and the deeper data in the Fennoscandian Shield and Southern Germany limits the veracity and application of these statistics. Permeabilities in the Molasse basin (σ_{logk} = 2.10 m^2) display the largest amount of scatter as compared to the Fennoscandian Shield Basin (σ_{logk} = 1.53 m^2) and Southern Germany (σ_{logk} = 1.36 m^2). The scatter in permeability correlates with tectonic activity, with low scatter in the tectonically inactive Fennoscandian Shield and higher scatter in the Molasse basin, which has undergone high rates of vertical motion in the Pliocene and Pleistocene (Genser *et al.* 2007; Cederbom *et al.* 2011). The large scatter and poor permeability–depth fit in the Molasse basin are also reflected in the bimodal distribution of the Molasse basin histogram in Fig. 6.

A KS test on near-surface data in the Fennoscandian Shield (average = –15.3 ± 1.38 m^2, n = 156) and South-

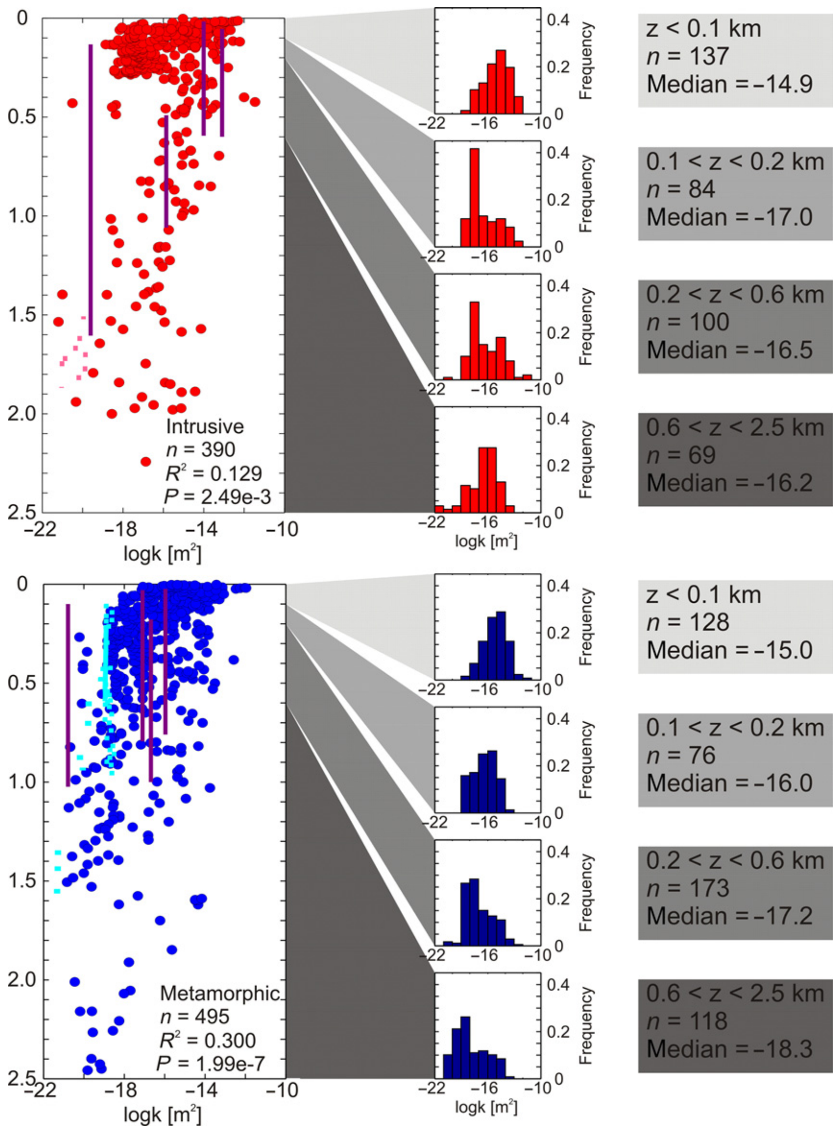

Fig. 5. The relationship between permeability and lithology for metamorphic (blue) and intrusive (red) rocks. All data points are mid-points of tested intervals. Pink rectangles indicate intrusive detection limits. Cyan rectangles indicate metamorphic detection limits. Purple lines indicate data points from tested intervals >500 m. Reported R^2 and *P*-values are for logarithmic fits through data. Histograms identify the permeability distribution in four depth ranges. From top to bottom: <100, 100–200, 200–600 and >600 m.

ern Germany (average = -14.2 ± 0.937 m^2, $n = 81$) shows that the two data sets are statistically dissimilar at 5% significance ($P = 1.5 \times 10^{-7}$). The deeper data in these regions show the same result ($P = 3.0 \times 10^{-13}$). In the light of the statistically similar near-surface result from the lithology analysis, this suggests that tectonic setting may be a stronger control on permeability in the near surface. This is consistent with the observation of Maloney *et al.* (2006) who noted a similar relationship in the Canadian Shield between stresses and depth. In their study, the near surface (<300–600 m) was much more influenced by local horizontal stresses, while stresses at depth reflected a stress regime determined by some distant boundary. Thus, local tectonics may be more important in the near-surface, less important at depth. We exclude the Molasse basin from this comparison due to the lack of near-surface data. In the 0.3- to 2.5-km-depth range where both Molasse basin and Fennoscandian Shield data are available, a KS test shows that the data sets are statistically dissimilar at 5% significance ($P = 8.8 \times 10^{-7}$). Considering tectonic setting provides useful insight into the applicability of a generalized logarithmic permeability–depth relationship. For example, applying a more general permeability–depth function to the data in the Molasse basin would be nonsensical due to the large amount of scatter inherent in the data.

Tectonic setting and lithology

Three tectonic setting–lithology combinations display no statistically significant permeability–depth relationship at 5% significance: Fennoscandian Shield intrusive ($P = 0.103$, $n = 279$); Fennoscandian Shield metamorphic ($P = 0.154$, $n = 236$); and Southern Germany intrusive

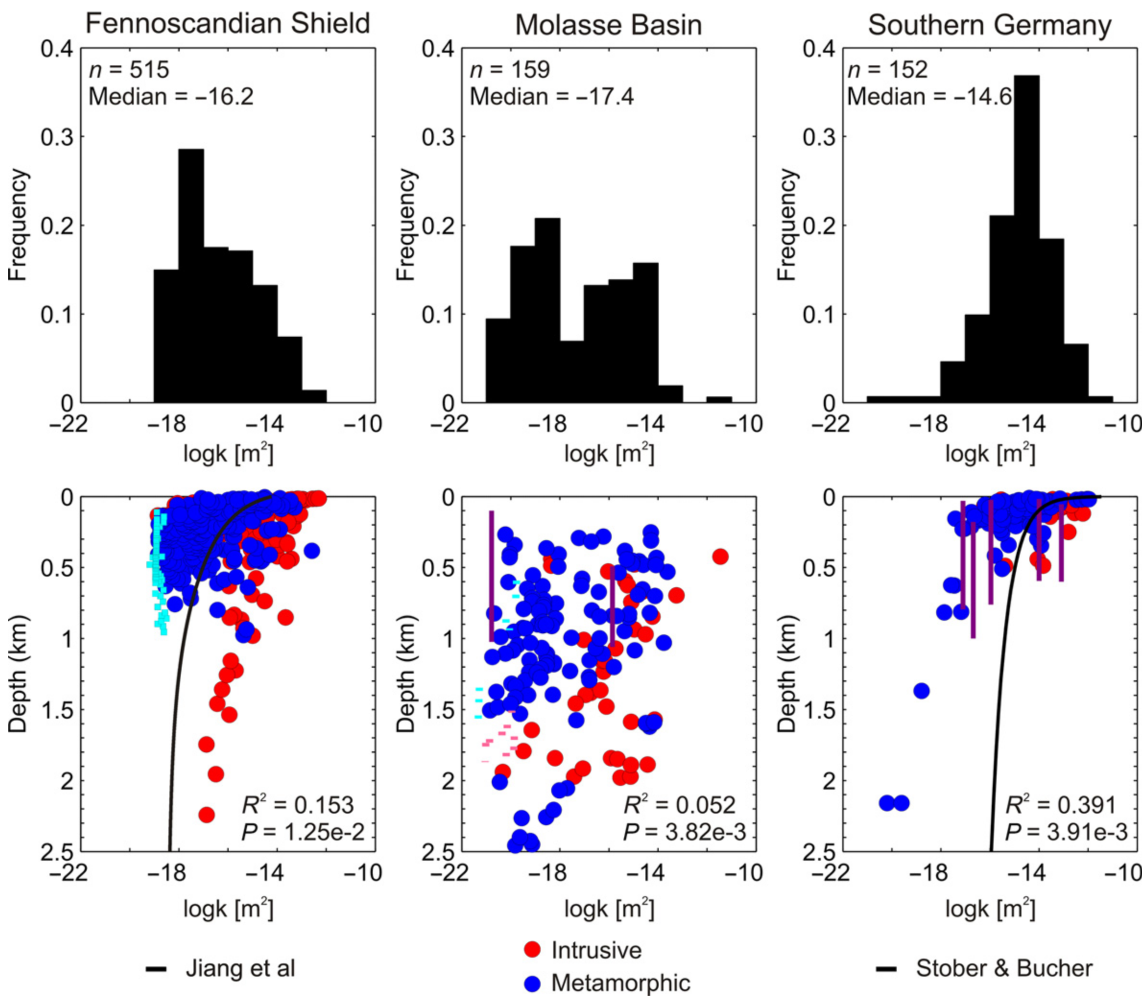

Fig. 6. The relationship between permeability and tectonic setting. Red points indicate intrusive rocks. Blue points indicate metamorphic rocks. Pink rectangles indicate intrusive detection limits. Cyan rectangles indicate metamorphic detection limits. Purple lines indicate data points from tested intervals >500 m. All data points are mid-points. Reported R^2 and *P*-values are for logarithmic fits through the combination of intrusive and metamorphic data. Grey lines are functions from literature (Stober & Bucher 2006; Jiang *et al.* 2010).

($P = 0.946$, $n = 45$). An important caveat to this observation is that the Fennoscandian metamorphic and Southern Germany intrusive data sets have no data below 1 and 0.5 km, respectively; further, the Molasse intrusive data include no data above 0.4 km (Fig. 7 and Table 2). KS tests on near-surface intrusive and metamorphic data in the Fennoscandian Shield and Southern Germany indicate that these data are statistically dissimilar at 5% significance ($P = 2.3 \times 10^{-5}$ and $P = 2.5 \times 10^{-4}$). KS tests indicate that near-surface metamorphic and intrusive data in the Fennoscandian Shield are statistically similar at 5% significance, while near-surface metamorphic and intrusive data in Southern Germany are dissimilar at just under 5% significance ($P = 4.9 \times 10^{-2}$). The similarity of near-surface data for multiple lithologies in a single tectonic setting relative to the dissimilarity between tectonic settings provides additional evidence that lithology may be a weaker control than tectonic setting. A KS test on Fennoscandian intrusive data and Molasse intrusive data in the 0.4- to 2-km interval ($n = 25$ and $n = 40$, respectively) indicates that these data are statistically similar at 5% significance ($P = 0.123$), suggesting that lithology may be a more important control on permeability for deeper data. Accounting for both tectonic setting and lithology defines stronger and more credible permeability–depth relationships, although categorization of data in this way decreases the number of points in each statistical analysis.

CONCLUSIONS

We compiled a large data set ($n = 973$) of permeability data from metamorphic and intrusive crystalline rocks in the shallow crust to depths of 2.5 km. The data were obtained mainly from three tectonic settings as follows: the

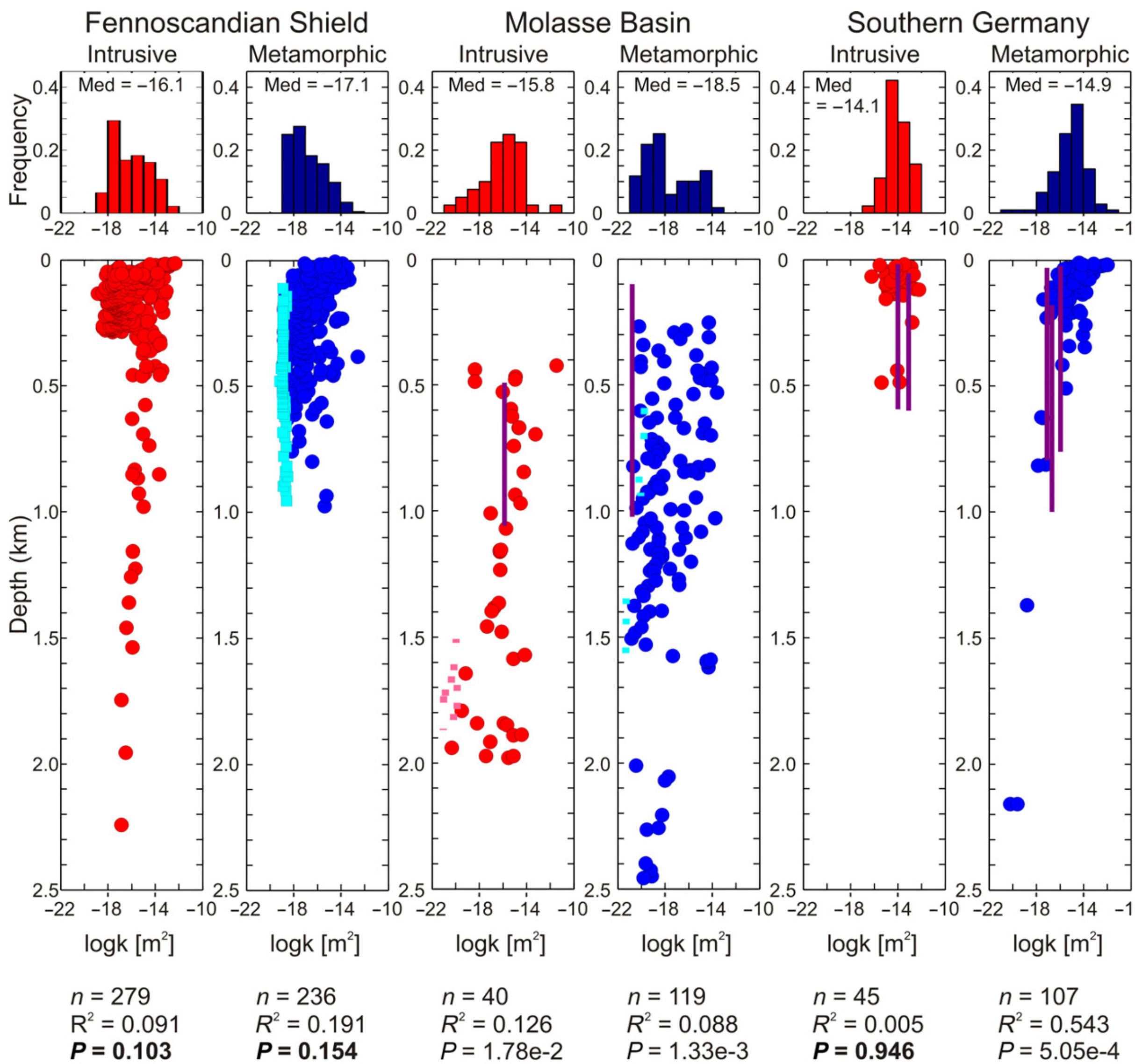

Fig. 7. The relationship between permeability and lithologies in different tectonic settings. Red indicates intrusive rocks. Blue indicates metamorphic rocks. Pink rectangles indicate intrusive detection limits, while cyan rectangles indicate metamorphic detection limits. Purple lines indicate data points from tested intervals >500 m. All data points are mid-points. Reported R^2 and *P*-values are for logarithmic fits through the data. Bolded *P*-values indicate data sets which fail the *t*-test at 5% significance. Histograms include text which indicates the median value of the distribution.

Molasse basin in Switzerland, the Fennoscandian Shield in Sweden and Southern Germany. We used trend analyses and Kolmogorov–Smirnov tests to quantify relationships between permeability and depth for the entire data set (excluding data measured under a detection limit and data from tested intervals greater than 500 m, $n = 885$) and subsets that distinguish tectonic settings and intrusive or metamorphic lithologies.

1 The trend analysis does not support a consistently applicable and generalizable relationship between permeability and depth in crystalline rock in the shallow crust ($z < 2.5$ km), in agreement with conclusions drawn previously by Brace (1980, 1984), Huenges *et al.* (1997), and Stober & Bucher (2006). A logarithmic fit to the entire data provides a very low R^2 value of 0.230 (Fig. 3). Although a *t*-test indicates a statistically significant decrease in permeability with depth at 5% significance, the low predictive power of the fitted function suggests that a generalized permeability–depth function should not be used in hydrologic and earth system models of the shallow crust without further justification.

2 Higher permeabilities are more common at shallow depths in crystalline rock (Fig. 3). The Kolmogorov–Smirnov test shows that near-surface permeabilities are statistically dissimilar (at 5% significance) from deeper permeabilities regardless of the depth cut-off (100–

1000 m). The average near-surface (<0.1 km) permeability (μ_{logk} = –15.0 ± 1.36 m^2, n = 265) is almost two orders of magnitude higher than the average of deeper permeability values (μ_{logk} = –16.8 ± 1.71 m^2, n = 624). Higher permeabilities at shallow depths could be due to fracture aperture, density or connectivity, hydromechanical responses due to lower vertical stresses and/or minimal fracture in-filling.

3 Lithology has a weak control on crystalline rock permeability at near-surface depths: the Kolmogorov–Smirnov test shows no statistical difference between metamorphic and intrusive rocks in the near surface at 5% significance. Intrusive rock permeabilities with depth are poorly described using a logarithmic function (R^2 = 0.129). Metamorphic rock permeabilities show a better agreement, but the predictive power of the function is still low (R^2 = 0.300). In both cases, a statistically significant decrease in permeability is apparent at 5% significance.

4 Tectonic setting has a stronger control than lithology on crystalline rock permeability in the near surface and may be a weaker control than lithology on crystalline rock permeability in the deeper subsurface (Fig. 6). A Kolmogorov–Smirnov test on near-surface data in the Fennoscandian Shield and Southern Germany (where near-surface data are available) indicates that these data are statistically dissimilar at 5% significance. On the contrary, a Kolmogorov–Smirnov test indicates that near-surface metamorphic and intrusive data in the Fennoscandian Shield are statistically similar, while near-surface metamorphic and intrusive data in Southern Germany are dissimilar at just under 5% significance ($P = 4.9 \times 10^{-2}$). Thus, tectonic setting appears to have more of an influence on permeability than lithology in the near surface. In the deeper subsurface, however, a Kolmogorov–Smirnov test on Fennoscandian intrusive data and Molasse basin intrusive data in the 0.4- to 2-km interval indicates that these data are statistically similar at 5% significance (P = 0.123), suggesting that lithology may have more influence on permeability in the deeper subsurface.

5 Tectonic activity may be a strong control on the variation in permeability with depth in crystalline rocks. Larger stress magnitudes in tectonically active regions may produce larger than expected fracture apertures at depth (Earnest & Boutt 2014; Rutqvist 2014), confounding a logarithmically decreasing permeability–depth relationship. The Molasse basin is an active tectonic region, as indicated by high rates of vertical motion since the Pliocene (Genser *et al.* 2007; Cederbom *et al.* 2011) (Fig. 1). Permeabilities in the Molasse basin are very scattered at depth, with the corresponding logarithmic function displaying an R^2 of just 0.052. While we did not explicitly explore the physical processes causing the higher values of permeability, the compiled data suggest that active tectonics may lead to higher permeabilities in the shallow crust, a hypothesis that may focus future research efforts.

6 The clearest permeability–depth relationships in crystalline rock are defined when lithology and tectonic setting are both accounted for (Fig. 7), although the smaller data sets available at this level of categorization limit the efficacy of the derived logarithmic fits. Three of six data sets that distinguish both tectonic setting and lithology demonstrate no statistically significant decrease in permeability with depth (Fennoscandian intrusive, Fennoscandian metamorphic and Southern Germany intrusive). Of the remaining three, the Molasse metamorphic and Molasse intrusive data display very low predictive power (R^2 = 0.088 and R^2 = 0.126, respectively), while the Southern Germany metamorphic data display the largest predictive power of any data set analysed (R^2 = 0.543).

DATA AVAILABILITY

The full data set is available from the research web page of the corresponding author and also on figshare.

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CONTENTS