GEOFLUIDS

Geofluids (2016) 16, 782–798 doi: 10.1111/gfl.12188

The biases and trends in fault zone hydrogeology conceptual models: global compilation and categorical data analysis

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ABSTRACT

To investigate the biases and trends in observations of the permeability structures of fault zones in various geoscience disciplines, we review and compile a database of published studies and reports containing more than 900 references. The global data are categorized, mapped, and described statistically. We use the chi-square test for the dependency of categorical variables to show that the simplified fault permeability structure (barrier, conduit, barrier–conduit) depends on the observation method, geoscience discipline, and lithology. In the crystalline rocks, the *in situ* test methods (boreholes or tunnels) favor the detection of permeable fault conduits, in contrast to the outcrop-based measurements that favor a combined barrier–conduit conceptual models. These differences also occur, to a lesser extent, in sedimentary rocks. We provide an estimate of the occurrence of fault conduits and barriers in the brittle crust. Faults behave as conduits at 70% of sites, regardless of their barrier behavior that may also occur. Faults behave as barriers at at least 50% of the sites, in addition to often being conduits. Our review of published data from long tunnels suggests that in crystalline rocks, 40–80% (median about 60%) of faults are highly permeable conduits, and 30–70% in sedimentary rocks. The trends with depth are not clear, but there are less fault conduits counted in tunnels at the shallowest depths. The barrier hydraulic behavior of faults is more uncertain and difficult to observe than the conduit.

Key words: fault zone, hydrogeology, permeability, statistics, structural geology, tunneling

Received 16 September 2015; accepted 13 July 2016

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INTRODUCTION

Globally, fault zones have been studied at many sites, and the permeability of rocks and their fracture networks have been estimated or tested *in situ* at different sampling scales, described by different metrics in structural geology (Faulkner *et al.* 2010), hydrogeology (Bense *et al.* 2013), and other geoscience and engineering disciplines. Caine *et al.* (1996) proposed qualitative and quantitative metrics to describe the fault zone permeability styles (also called permeability structure or architecture), but despite having more than 1000 citations to the general concept of barrier–conduit, the proposed quantitative metrics have been only used in small number (approximately 10) of studies (e.g., Brogi 2008; Ganerød *et al.* 2008; Liotta *et al.* 2010). There is also ambiguity in the use of the qualitative metrics and conceptual models and the terminology (Shipton *et al.* 2013). It has been suggested by Bense *et al.* (2013) that multidisciplinary data integration are needed to help understand the fluid flow processes along fault zones.

In this study, a *simplified permeability structure* of a fault zone (following Caine *et al.* 1996) is used as a conceptual framework to classify the results from the compiled research sites. To compare a large number of sites and observations, a simple 'end-member' type of conceptual model that can be applied at the majority of the sites is appropriate and this has been carried out by other authors. For example, at the Yucca Mountain nuclear repository site, Dickerson (2000) divided faults into simple barrier/conduit/conduit–barrier/none (offset only) categories. Similarly, Aydin (2000) used the categories of transmitting (conduit), sealing (barrier), vertically transmitting and laterally sealing (conduit–barrier), and sealing or transmitting intermittently (transient conduit or barrier). A more fine categorization (e.g., weak or strong barrier, barrier/conduit permeability ratio), or a quantitative mapping of permeability distributions and discrete fracture network models as proposed by Caine & Forster 1999 is not available at the majority of sites, and this would result in too small counts of data to be useful for statistical analysis. Therefore, we use only three categories to count the permeability structures: (i) barrier, (ii) conduit, and (iii) barrier–conduit.

The definition of a conduit used here is where fault rock is more permeable than the protolith and the conduit geometry is usually conceptualized parallel to the fault plane and within the damage zone, in the majority of studies that we reviewed. The barrier is defined where the permeability zone somewhere in the fault structure affects the transverse flow of groundwater across the fault (the barrier permeability is less than the protolith). A barrier–conduit is where both the barrier and the conduit are present, as defined earlier. In this study, we are not comparing parts of fault zones in this study (e.g., fault core versus damage zone), or assess the magnitude permeability (e.g., how leaky is a barrier). For the purposes of counting of barrier and conduit frequencies at the global sites, these three categories (barrier, conduit, barrier–conduit) are exclusive. The barrier category means barrier only, where there was no observation of a conduit behavior of the fault. Similarly, the conduit category means conduit only (no observation of barrier effect). A fourth category was initially used for fault zones with 'no observable hydrogeological impact', but the counts of such sites were too small to use in the statistical analysis together with the other data. It appears that the studies report a 'positive result' where the fault has been characterized or tested successfully to some extent. Later in the study, we present proportions of conduit faults along 30 large tunnels. The faults that are not counted as conduits may be barriers or may have the same permeability as the protolith, although we could not assess these properties from inflow data in tunnels alone.

The objective of this research is to quantify the observational biases of fault zone hydrogeology and describe global occurrences and trends in the barrier, conduit, and barrier–conduit behavior. To do this, we analyze a large, new global dataset of published data and inferred conceptual models of fault zone hydraulic behavior. Statistical tests are used to detect biases of different test methods and of collections of methods across geoscience disciplines, and the results are used to discuss the knowns and unknowns of the fault zone permeability structures in Earth's the brittle crust.

METHODS

Data sources

For our analysis, we review published data and interpretations in multidisciplinary geoscientific and engineering literature, compiled from different geoscience fields, including hydrogeology, structural geology, reservoir and geotechnical engineering, and related industries. Due to the large number of data sources used, we provide a full listing of the references used and the database containing the fault zone attributes in the supplementary information associated with this article, while the reference list that follows this article covers only the citations used in the text and one table. The data compilation is an example of secondary data analysis to answer new questions with older existing data (Glass 1976). This contrasts with primary data analysis, which is site-specific hydrogeological, structural, geothermal and other analysis of primary data (observations, tests, models, etc.). It is important to use a wide range of databases and search methods in meta-analysis of existing research data (Whiting *et al.* 2008). We use databases of academic journals, national geological surveys and organizations, atomic energy waste management and research organizations, and technical reports from industries. This study looked primarily publications in English, and less numerous papers and reports translated from Japanese, French, German and Italian. We reviewed at least 1817 publications and found that 914 had references to fault zone permeability (Table 1). Smaller subsets that satisfied various queries by selected categories were used for statistical analysis (698 for comparing results between geoscience disciplines). The following sections explain the data sources and methodology.

Data sources used in statistical analysis

Structural geology studies are typically at outcrops due to easier access, although scientific deep drilling is also an important component (e.g., reviews in Juhlin & Sandstedt 1989; Townend & Zoback 2000). In outcrop studies, the data collection is usually focussed on small-scale probing and testing of rock matrix permeability on outcrop samples or shallow probe holes (Okubo 2012; Walker *et al.* 2013). There are only a few studies of statistical analyses of

Table 1 (a) Counts of fault study sites reviewed and used in statistical analysis from five geoscience disciplines. (b) Counts of fault sites reviewed from geothermal and geophysical data sources but not used in statistical analysis.

	Refs.	Used in analysis	Barrier only	Conduit only	Barrier & Conduit
(a) Geoscience discipline					
1) Structural Geology	231	187	59	42*	37
2) Hydrogeology	490	308	87	164	57
3) Tunnels Engineering	175	110	10	70	30
4) Mine and Dam Eng.	40	42	10	24	8
5) Hydrocarbon Res.	76	52	22	23	7
Subtotal (1 to 5)	1012	699	188	323	139
(b) Data reviewed but not used in statistical analysis due to lack of barrier					
6) Geothermal Res.	700	143	3	140	0
7) Geophysics	105	73	0	66	0
Total (1 to 7, all sites)	1817	914			

*present-day permeability distribution (does not include paleo-conduits).

hundreds of outcrop samples (Balsamo & Storti 2010). Permeability structures are also inferred from porosity and fracture distributions (Matonti *et al.* 2012; Mitchell & Faulkner 2012) and empirical laws or comparisons to permeability samples.

In this study, the 'hydrogeology' category includes aquifer studies and research sites in fractured and faulted rocks of any lithology. The hydrogeology category has the largest sample size of fault zones, typically at depths less than 1000 m. Permeability estimates and fault hydraulic behaviors are typically tested through borehole tests, observations of natural hydraulic and temperature gradients near faults, and through the geochemistry of waters (e.g., review by Bense *et al.* 2013). Hydrogeological tests (e.g., aquifer tests) are carried out in all other geoscience disciplines, but we chose to separate the other geoscience disciplines to test statistically whether there are differences between them in how fault zones are viewed.

The tunnel engineering category includes long transportation tunnels and water transfer tunnels (hydroelectric projects, aqueducts) and is mostly in the domain of geotechnical and civil engineering, with a strong hydrogeology component. The permeability of fault zones is 'detected' usually by observations, such as inflows of water during tunnel excavation, in pretunneling drilling programs.

The category of 'mines and dams' refers to large excavations that are not long transportation tunnels, although both dams and underground mines involve tunnels, although at smaller diameters usually than the transportation tunnels. Dam foundation works involve a large number of drillhole-based injection or pumping tests and fracture mapping. At open-pit mines, the data quality varies greatly, but for fault zones, it is usually limited to seepage observations or water table mapping.

The category of hydrocarbon reservoirs includes papers presenting conceptual models for fault hydraulics in sedimentary basins, although this category is very limited because data repositories are generally held privately by the petroleum industry. In sedimentary basins, there has been a focus of studies on barrier faults and reservoir compartmentalization (e.g., Jolley *et al.* 2010). Reservoir outcrop analog studies (e.g., Antonellini & Aydin 1994; Solum *et al.* 2010) are included in the structural geology category. Fault conduits have been inferred from geomechanical analysis in studies of fractured hydrocarbon reservoirs (Gartrell *et al.* 2004; Hennings *et al.* 2012), in sedimentary and faulted crystalline rocks below sedimentary basins (Petford & McCaffrey 2003).

Data sources reviewed but not used in statistical analysis

Geothermal drilling is potentially a good source of data on fault conduits, for which we reviewed approximately 700 papers as part of an ongoing study on this topic (Scibek *et al.* 2015). Descriptions of conceptual and numerical models of whole reservoirs are commonly published (Bjornsson & Bodvarsson 1990; O'Sullivan *et al.* 2001). Most of the permeability data collected by the industry is not published, while journal papers usually present only conceptual models (e.g., Serpen 2004) or results of numerical models (Magri *et al.* 2010). Fault conduits that discharge hydrothermal fluids are very common, and due to their large number and global distribution, warm- and hot-springs can provide useful insights into structural controls and the magnitude of permeability of conduits (Muraoka *et al.* 2006; Rowland & Simmons 2012; Faulds & Hinz 2015). We also reviewed published estimates of hydraulic diffusivity from cases of reservoir-induced seismicity along faults (Gupta 2002; Talwani *et al.* 2007), and naturally occurring migrating earthquake swarms (El Hariri *et al.* 2010; Chen *et al.* 2012; Okada *et al.* 2015). The conceptual models of fluid migration assume fault conduits and give no information about fault barriers. In both categories, the lack of representative fault barrier counts prevented us from using these data in the statistical analysis.

Data synthesis and fault zone attribute counting

Observation method categories

In this study, we include sites where the inferred fault zone permeability structure was supported by permeability tests or hydraulic tests or other fluid flow phenomena along and across fault zones (e.g., natural tracers, geochemical properties), or a clearly presented conceptual model with supporting evidence. Numerical models of particular sites were only treated as supporting evidence and numerical models that were non-site-specific (hypothetical) or not robustly calibrated were not used. Papers describing fault zone morphology, lithology, and structure without any permeability tests were not used. The different data sources differ in their preferred methods of observations, their scales of measurement, depths of samples, and purpose of investigation of fault zones and nonfaulted rocks. Consequently, each site was classified by observation type, depending on the type of test and the scale of test. In all the categories, the frequencies (counts) were tabulated for the occurrence of inferred simplified fault zone permeability structure conceptual models, forming the basis of our statistical analysis. The 'raw data' counts were at first divided into more than 40 subcategories of measurement methods, but after preliminary analysis we decided to aggregate the data into six categories of observation type. For example, the matrix permeametry measurements or estimates were grouped together, small-scale borehole interval hydraulic tests were grouped, large-scale hydraulic tests that measure a large volume of rock were also grouped, and so on.

The total number of data points for observation methods totaled 785, which is greater than the total number of data from different published references (699). The excess of 'data points' in the counts of observation method data is because in 73 studies there were more than one observation method employed to probe the fault hydraulics, and another 50 references had unspecified observation method or method that did not fit in the main categories or the results were not conclusive. All study sites were treated equally, not weighted or adjusted based on perceived data quality, test method or scale of investigation. There are obvious differences between the data from site to site, but it is difficult to objectively assign a quality index, and this may be addressed in future studies. We counted the data in conceptually exclusive categories, although in reality there are an unknown number of sites where fault zone permeability structure were mis-classified (e.g., barrier or conduit exists was not detected, an example of statistical Type II error). The categories of observation methods are as follows:

(1) drill core and outcrop samples (rock matrix permeability tests, porosity–permeability conversions on matrix rock),
(2) borehole hydraulic tests (including slug and packer tests on borehole intervals, drill stem tests),
(3) borehole hydraulic tests at larger scale involving pumping tests and well production rates,
(4) hydraulic head or pressure difference observations across fault zones,
(5) water properties across fault zones (chemistry, temperature, or tracers),
(6) tunnel inflow observations and drawdowns around tunnels with fault zone interactions.

Geoscience discipline categories

The data sources are categorized by geoscience or engineering discipline. The geoscience disciplines can be thought as grouped sets of methods and approaches to studies of fault zones and not exclusively a study discipline in the traditional sense. Initially, all the reviewed sites were grouped into seven categories for exploratory data analysis (Table 1), but the two categories *geothermal reservoirs* and *geophysics* contained only fault conduits, and thus we excluded these two categories from statistical tests to avoid biasing the results with too many fault conduit spurious results where categories contain too few data counts (Cochran 1952). When counts are too low or zero, the chi-squared test is less conservative and tends to produce a significant result. In the five remaining geoscience discipline categories, there were 650 data sources describing the simplified fault zone permeability structures. The maps presented in Fig. 1 are, to our knowledge, the first such maps showing globally the locations of fault zone test sites. The data are shown by categories of geoscience discipline and the simplified permeability structure.

Lithology categories

The geological conditions were reviewed at the fault study sites to summarize the dominant lithological units in the database. These included igneous intrusive rocks (mostly granitic), metamorphic rocks (usually it was gneiss), volcanic rocks (usually basalt or tuff, and we separate these into subcategories), and sedimentary rocks (heterogeneous). In the results, we present counts for these categories. For the statistical tests, described in the next section, only the most general lithological categories are used: (i) crystalline rocks and (ii) sedimentary rocks. At the time of writing of this study we were able to summarize only the most general lithological descriptions in the majority of study sites that we reviewed.

Categorical data analysis with chi-square test

Hypotheses tested

We frame the statistical analysis and hypothesis test in terms of the response variable *simplified fault zone permeability structure* and the explanatory variables: the observation method, geoscience discipline, and lithological categories. The null hypothesis is that there is no dependence of the response variable on the explanatory variable, and the alternate hypothesis is that there is a dependence. The underlying assumption is that these observations can be treated as samples from a very large global 'population' of fault zones, and that these samples are close to being random samples and can be treated statistically. Four hypotheses were tested for the dependence of the simplified fault zone permeability structure on:

(1) observation method,
(2) geoscience discipline,
(3) lithological category (crystalline or sedimentary rocks),
(4) geoscience discipline (separately for crystalline and sedimentary rocks).

In hypothesis 4, we further explore the control of lithology on the test for dependence between the fault zone permeability structure and the geoscience discipline, but after filtering the data into two main lithological categories: crystalline rocks and sedimentary rocks.

Statistical methods

We use the Pearson chi-square test for independence of variables (Pearson 1900). The test determines whether there is a difference between two categorical variables in a sample which reflects real difference between these two variables in the global dataset (review by Voinov *et al.* 2013). This test has been used in medical, social, and natural science fields to evaluate interactions between the categorical variables (Lewis & Burke 1949; Delucchi 1983). In hydrogeology, it has been used to compare fracture frequencies in lithological categories at a site in South Carolina containing a fault zone (La Poite 2000). This test makes no assumptions about the shape of the population distribution, but it assumes random sampling from the

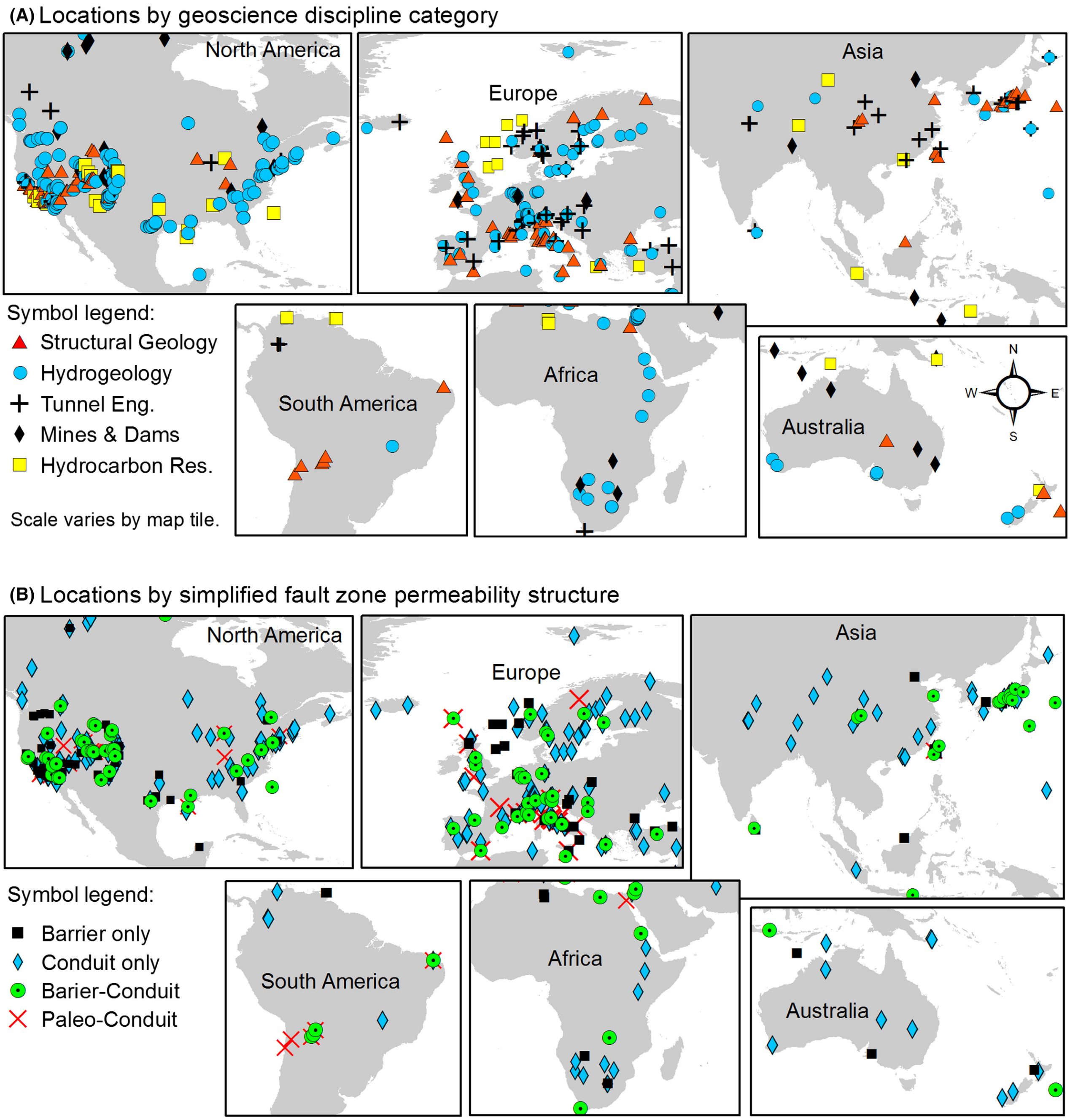

Fig. 1. Locations of reviewed fault zone study sites categorized by (A) geoscience discipline of data source, (B) simplified conceptual model of fault zone permeability structure.

population and a nominal or ordinal statistical scale of measurement. The simplified and applied methodology of hypothesis testing and chi-square calculation is explained in many textbooks (e.g., Agresti 2002; Howell 2011). The underlying assumption is that the observations represent random samples from a very large global 'population' of fault zones. The *contingency table* is used to show cross-classification of categorical variables of observed frequencies (counts), using notation after Agresti 2002:

$$\hat{\mu}_{ij} = \frac{n_{i+} \times n_{+j}}{n} \tag{1}$$

where $\hat{\mu}_{ij}$ is the expected frequency at table cell with row i and column j, $n_{i+} \times n_{+j}$ is the product of marginal totals in the table (n_{+i} for rows totals and n_{+j} for column totals), and n is the total count of all data in the table. The chi-square statistic (χ^2) is calculated as the sum (across rows and columns) of normalized differences between observed and expected frequencies (for example see Table 2):

Table 2 Fault zone permeability structure model counts by categories of observation method: contingency table of observed, expected frequencies, and calculated chi-square terms and standardized Pearson residuals. The categories of observation method table columns are as follows: (a) drill core and outcrop samples; (b) borehole interval hydraulic tests (packer, slug); (c) borehole interval large hydraulic tests (pump or injection); (d) hydraulic head or pressure differences across fault; (e) water chemistry, temperature, natural tracers; (f) tunnel inflow or drawdown.

	(a)	(b)	(c)	(d)	(e)	(f)	Totals	(a)	(b)	(c)	(d)	(e)	(f)
Observed frequencies								Expected frequencies					
Barrier	51	15	13	84	22	9	194	28	43	19	37	38	30
Conduit	32	120	47	19	97	85	400	59	89	38	75	78	61
Barrier–conduit	32	39	15	45	34	26	191	28	42	18	36	37	29
Totals	115	174	75	148	153	120	785						
Chi-square terms and chi-square result								Standardized Pearson residuals					
Barrier	17.9	18.2	1.7	61.5	6.6	14.4	120.3	5.3	−5.6	−1.6	10.0	−3.3	−4.7
Conduit	12.1	11.1	2.0	42.2	4.6	9.3	81.3	−5.4	5.4	2.1	−10.3	3.4	4.7
Barrier–conduit	0.6	0.3	0.6	2.2	0.3	0.4	4.3	0.9	−0.7	−0.9	1.9	−0.7	−0.7
							$\chi^2 = 206$						

$$\chi^2 = \sum_i \sum_j \frac{\left(n_{ij} - \hat{\mu}_{ij}\right)^2}{\hat{\mu}_{ij}} \quad (2)$$

The shape of the chi-square sampling distribution depends on degrees of freedom, calculated from the product of (#rows - 1) by (#columns -1) in the contingency table. The strength of the association of these variables can be shown with a cell-by-cell comparison of the observed and expected frequencies using the standardized Pearson Residual$_{ij}$, where the sample marginal proportions are $\pi_{i+} = n_{i+}/n$ and $\pi_{j+} = n_{+j}/n$:

$$\text{Pearson Residual}_{ij} = \frac{n_{ij} - \hat{\mu}_{ij}}{\left[\hat{\mu}_{ij}(1-\pi_{i+})(1-\pi_{+j})\right]^{0.5}} \quad (3)$$

The results of the chi-square test are evaluated by calculating the left-tailed probability of having the computed χ^2 value, at a specified degrees of freedom, to the probability threshold of 0.001 (in this paper), or any other chosen level of significance. If the calculated probability is <0.001 (usually for a large χ^2), then the difference between the observed distribution and the expected distribution is too large to be a result of random variation, and the null hypothesis will be rejected. For individual entries (table cells) in the contingency table, an absolute value of the Pearson Residual greater than 2 or 3 indicates a lack of fit of the null hypothesis (Agresti 2002).

RESULTS

Hypothesis 1 test (simplified fault zone permeability structure versus observation method)

The chi-square statistic is 206 and the left-tailed probability of having this χ^2 at 10 degrees of freedom is 5×10^{-39}, which is less than probability threshold of 0.001. Therefore, there is strong evidence of association between the inferred permeability structures of fault zones and the observation method. This is apparent from the different shapes of the histograms of these categorical variables (Fig. 2A). The Pearson residuals exceed the value of 3 in about half of the

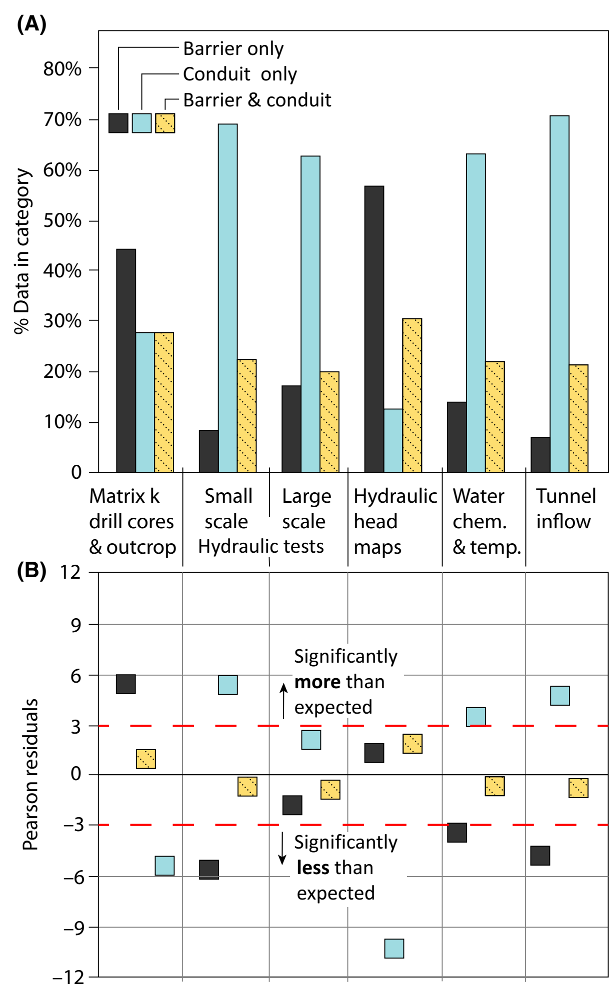

Fig. 2. Summary histograms for the simplified fault zone permeability structures in observation method categories: (A) histograms relative frequencies by observation method, and (B) comparing the observed to expected frequencies of fault zone simplified permeability structures using the calculated Pearson residuals from chi-square analysis of categorical data.

table cells, indicating significant from the frequencies that would be expected for a randomly-distributed variable sampled from a population that has the expected frequencies calculated using Equation 2 and listed in Table 2. (Fig. 2B).

The following observations are made about the results:

(1) Observations based on permeability from drill cores and outcrops favor the combined barrier–conduit permeability structures.
(2) Borehole test results at small scale and large scale suggest similar frequencies of fault conduits and barriers. Both favor the conduit permeability structure, and both provide fewer barrier faults than would be expected from a random sample taken from this whole dataset (assuming that it represents the population of fault zones globally).
(3) The methods relying on hydraulic head or pressure differences across fault zones result in more than expected barrier fault models, less than expected conduit fault models, and approximately the expected frequency of combined barrier–conduit fault models.
(4) The observations of water chemistry and tracers across fault zones produce the expected results of the frequencies of conduit faults and barrier–conduit faults, except with less than expected barrier-only faults.
(5) In tunnels, the observations relying on inflows result in more than expected conduit faults, but can be poor at detecting the barrier faults.

Hypothesis 2 test (simplified fault zone permeability structure versus geoscience discipline)

The Pearson chi-square test results was $\chi^2 = 50$ ($P = 1.5 \times 10^{-8}$), suggesting an association between the simplified fault zone permeability structure and the geoscience discipline. The histograms in Fig. 3A show graphically the differing counts, but the Pearson residuals (Fig. 3B) only exceed the absolute value of 3 in two categories and are generally within the acceptable limits for other categories. Therefore, the dependence on the geoscience discipline is not as strong as for the observation method, perhaps because some observation methods are used in all geoscience disciplines. The analysis was carried out on five geoscience disciplines, as was mentioned earlier. This avoids distorting the expected frequencies for the whole table (i.e., the results tend to be more 'significant' or extreme in chi-square value when the seven categories are used with the very different frequencies or counts). The contingency table (Table 3) has 2 cells with frequencies <10 but >5, that is deemed to be acceptable.

The following observations can be made:

(1) In the structural geology category, there are less conduit faults and more combined barrier–conduit faults than expected for the whole dataset.

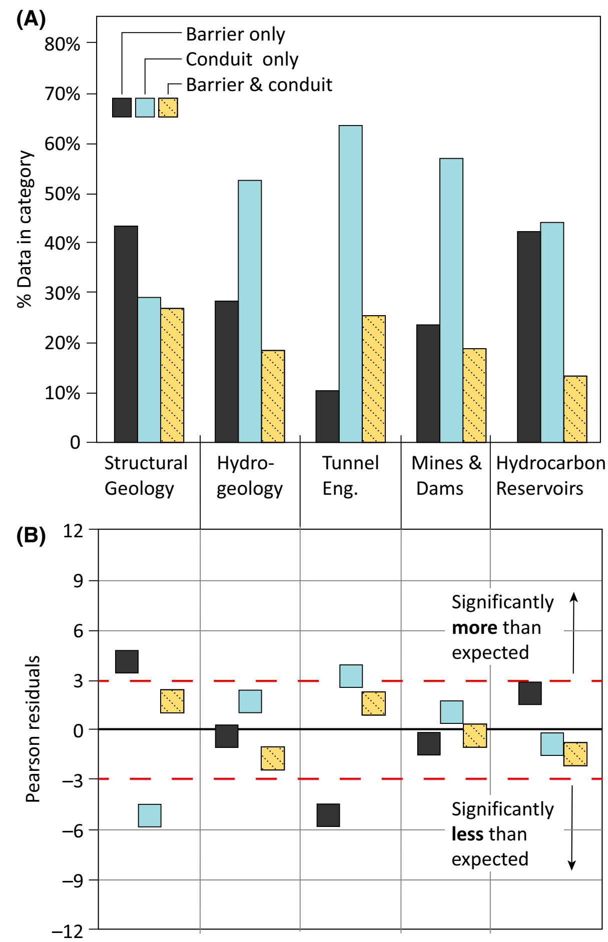

Fig. 3. Summary histograms for the simplified fault zone permeability structures in geoscience discipline categories: (A) histograms of relative frequencies by geoscience discipline, and (B) comparing the observed to expected frequencies of fault zone simplified permeability structures using the calculated Pearson residuals from chi-square analysis of categorical data.

(2) In the categories of mine and dam engineering and hydrogeology, the occurrences of fault permeability structures are approximately as expected.
(3) The tunneling engineering category has smaller than expected frequency of barrier faults and much more than expected conduit faults.
(4) In the category of hydrocarbon reservoirs, the limited data highlights the well-known occurrence of barrier faults in sedimentary rocks.

Hypothesis 3 test (simplified fault zone permeability structure versus lithology)

To investigate the effects of lithology on the previously determined results from hypotheses 1 and 2, we compared the frequencies of the simplified fault zone permeability structures between two main lithological categories:

Table 3 Fault zone permeability structure model counts by categories of geoscience discipline: contingency table of observed, expected frequencies, and calculated chi-square terms and standardized Pearson residuals.

	Structural geology	Hydrogeology	Tunnel. Eng.	Mining & Dams	Hydrocarbon Reservoirs	Totals	Structural geology	Hydrogeology	Tunnel. Eng.	Mining & Dams	Hydrocarbon Reservoirs
Observed frequencies							Expected frequencies				
Barrier	59	87	10	10	22	188	40	89	32	12	15
Conduit	42	164	70	24	23	323	69	153	55	21	26
Barrier–conduit	37	57	30	8	7	139	30	66	24	9	11
Totals	138	308	110	42	52	650					
Chi-square terms and chi-square result							Standardized Pearson residuals				
Barrier	9.1	0.0	15.0	0.4	3.2	27.7	4.0	−0.4	−5.0	−0.8	2.2
Conduit	10.3	0.8	4.3	0.5	0.3	16.2	−5.1	1.7	3.2	1.0	−0.8
Barrier–conduit	1.9	1.2	1.8	0.1	1.5	6.5	1.8	−1.7	1.7	−0.4	−1.5
						$\chi^2 = 50$					

Table 4 Comparing the frequencies of occurrence of data within lithological categories. The table shows the counts of fault zone simplified permeability structures, and the counts of fault zone sites within geoscience disciplines that have the specified lithology of protolith.

	Simplified permeability structures					Geoscience disciplines				
Lithology	Barrier	Conduit	Barrier & Conduit	Total	% Conduit (any)	Structural geology	Hydrogeology	Tunnel. Eng.	Mining & Dams	Hydrocarbon Reservoirs
Sedimentary rocks	140	138	85	363		122	226	67	22	47
	39%	38%	23%		61%	68%	59%	47%	55%	92%
Crystalline rocks	23	147	57	227		58	157	76	18	4
(metamorphic and igneous 'basement')	10%	65%	25%		90%	32%	41%	53%	45%	8%
Other subcategories of lithology										
Granitic rocks	11	76	29	116		35	86	43	4	3
	9%	66%	25%		91%	19%	23%	31%	10%	6%
Basalt rocks	14	19	6	39		9	25	11	6	2
	36%	49%	15%		64%	5%	6%	7%	15%	4%

sedimentary rocks and crystalline rocks. The latter refers here to the metamorphic and igneous 'basement' rocks. We also summarized two other common subcategories of lithology of interest: granitic rocks and extrusive igneous rocks (basalts, andesites, etc.) (Table 4). The histograms are shown in Fig. 4A. The geoscience disciplines that have the most fault zones in the crystalline rocks are tunnel engineering, mines and dams, and hydrogeology (between 40% and 50%), as shown in Fig. 4B). Structural geology field sites are 68% in sedimentary rocks, and more than 90% of hydrocarbon reservoir studies compiled in this analysis are in sedimentary rocks.

The chi-square test returns a significant result ($P < 0.001$) with a large χ^2 of 162, suggesting that the differences seen in the histograms between the sedimentary and crystalline rocks are significant. Other useful observations are as follows:

(1) In sedimentary rocks, barrier and conduit faults are equally common (approximately 38%).
(2) The occurrence of 'any conduit', that is the sum of the two exclusive categories 'conduit only' and 'barrier and conduit', is 61% in the sedimentary rocks, and up to 90% in the crystalline rocks. Since usually only small parts of fault zones have been tested at each site, these counts and percentages don't imply that entire fault zones at large scale act as conduits, but that some parts of the fault zones do and that this seems to be common.
(3) The proportion of fault conduits in the subcategory of granitic rocks is about the same as in the main category of crystalline rocks. The fault conduit proportions in basaltic rocks are approximately the same as in sedimentary rocks.

Hypothesis 4 test (as in Hypothesis 2 but for sedimentary and crystalline rocks separately)

In the crystalline rocks (Table 5a), there are significant differences between the geoscience disciplines ($\chi^2 = 37$, $P = 9 \times 10^{-8}$). There are 29% of barrier-only faults inferred in structural geology studies compared to only 5% to 6% in hydrogeology and tunneling. Conduit-only faults

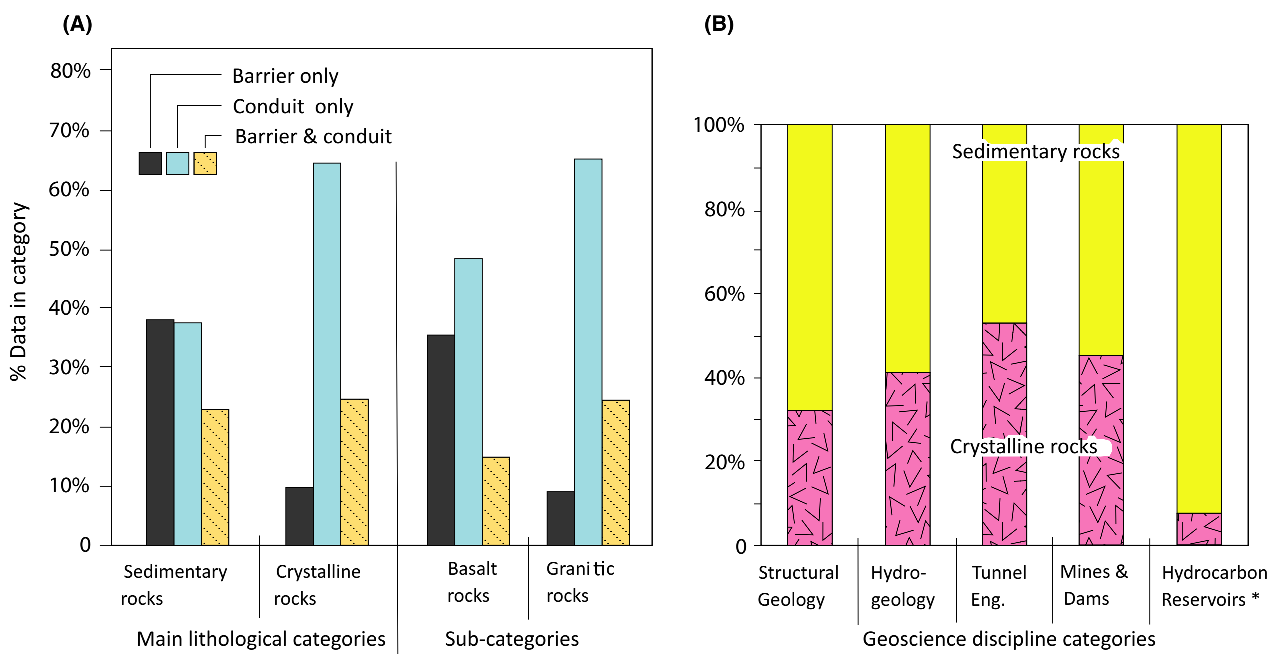

Fig. 4. Comparing the (A) histograms of fault zone simplified permeability structures by lithology categories, and, (B) proportion of sample sites that have the dominant lithology in sedimentary or crystalline rocks in subsets of data by geoscience discipline.

Table 5 Comparing the frequencies of occurrence of permeability structures for three geoscience disciplines (Structural geology, Hydrogeology, Tunnel engineering) separately for the crystalline rocks (metamorphic and igneous), and for the sedimentary rocks.

	(a) Crystalline rocks (metamorphic & igneous)					(b) Sedimentary rocks				
Geoscience discipline	Barrier	Conduit	Barrier & Conduit	Total	% Conduit (any)	Barrier	Conduit	Barrier & Conduit	Total	% Conduit (any)
Structural geology	12	15	14	41		44	28	22	94	
	29%	37%	34%		71%	47%	30%	23%		53%
Hydrogeology	5	86	16	107		66	61	39	166	
	5%	80%	15%		95%	40%	37%	23%		60%
Tunneling	4	36	22	62		6	25	13	44	
	6%	58%	35%		94%	14%	57%	30%		86%

dominate in hydrogeology (80%). The total count of any conduit fault is high in all geoscience disciplines (>70%) but is the highest in hydrogeology and tunneling (95%). In the sedimentary rocks (Table 5b), there are no significant differences between the counts of fault barriers and conduits in structural geology and hydrogeology ($\chi^2 = 1.6$, $P = 0.18$). There are about 30% and 37% for conduits and 47% to 40% for barriers. Tunneling counts show the largest differences from expected frequencies, favoring more conduits (57%), but we have low counts (6 in barrier category) for tunneling category in sedimentary rocks and this difference should be viewed with caution. We use a representative or 'average' conceptual model for each site, including tunnels, thus the in-tunnel statistics of how many faults are crossed and how many caused water inflows are not included in the global statistics up to this point. Overall, the total percentage of fault conduits (any conduits calculated from the sum of category totals for 'conduit only and 'conduit & barrier') in sedimentary rocks is about 50% to 60% in hydrogeology and structural geology geoscience disciplines, and more than 80% in tunnel engineering (Fig. 5).

Estimating the proportion of fault conduits from long transportation tunnels

Faults have been known to be the dominant water inflow points in most tunnels (e.g., Goodman & Bro 1987), and numerous papers were published already about the statistics of fault properties in tunnels (Masset & Loew 2010, 2013). Faults crossed by tunnels can be complex structures with multiple fault cores (e.g., Lutzenkirchen 2002; Fasching & Vanek 2013). Here we use the published inflow summaries from 30 long transportation tunnels, as listed in

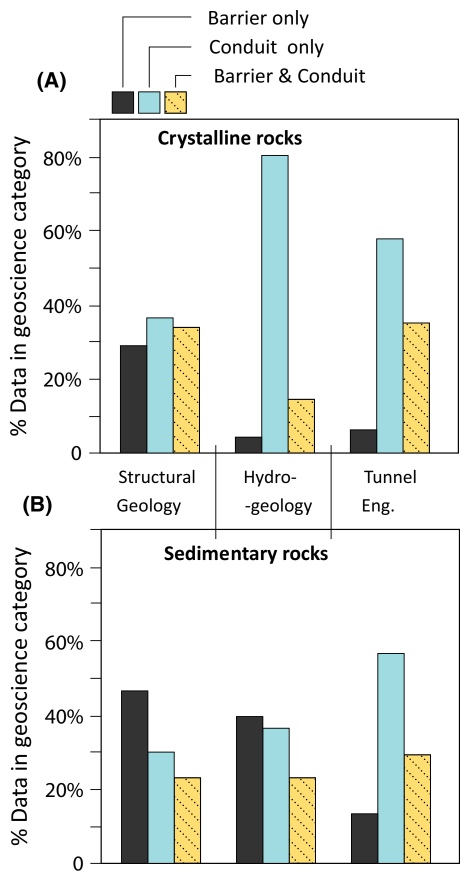

Fig. 5. Comparing the proportions of barrier, conduit and barrier–conduit faults in the main lithological categories: (A) crystalline rocks, (B) sedimentary rocks.

Table 6, to provide another estimate of the relative occurrence of fault zone conduits. This list of tunnels was not preselected, but includes as many tunnels as we could find during this global review that were described sufficiently to be able to count the number of major fault zones that produce water inflows during the tunnel excavation. In each tunnel the percentage of fault zones that acted as water conduit was estimated relative to the total number of 'major' fault zones (or groups of faults forming fault zones) crossed by the tunnel, taken from published tunnel-geologic cross sections that also showed water inflow points. The limitation of this survey is that there was no information about fault barriers in most of these reports and we did not count them. We also note that a lack of reported inflow while crossing a fault zone does not imply that it is a barrier because the fault may be of the same bulk permeability as the host rock and may be heterogeneous.

The tabulated results in Table 6 show that the proportion (percentage) of fault zones that were major conduits for water varied from 30% to about 90%, with a median of about 50%, and some dependence on lithology. In tunnels excavated in sedimentary rocks, there is a suggestion that the proportion of fault conduits is less than in the crystalline rocks (about 30% to 80% and a median of about 50%). We return to these results and present them graphically in the following discussion. Up to this point, we have presented the global statistics of conduits and barriers that had no spatial component (no length or area) because all samples were reduced to simple counts within categories. However, in the tunnel data, there is a spatial component because the inflow points occur along the length of the tunnel and at some depth, although the data here are simplified to show the average depth of the tunnel.

DISCUSSION

Biases in observing the fault zone permeability structure

The difference in observed frequencies of inferred fault permeability structures among the geoscience disciplines is partly explained by the choice of preferred test methods for each discipline. Alternatively, if the study sites are not randomly sampling fault properties in the Earth's upper brittle crust, the differences may be attributed to lithological, tectonic, and depth conditions. The differences occur partly because of geological conditions, and here we argue that it is also partly caused by biases in observation methods employed.

At outcrop studies of analogs of faulted hydrocarbon reservoirs, the matrix permeability tests and fracture mapping suggest a balanced barrier–conduit model because the fault core can be tested effectively at that scale ('Drill core & outcrop samples' category in Fig. 2). The faults are heterogeneous and it is difficult to assign only one simple category of the permeability structure to describe the hydraulic behavior (Shipton *et al.* 2002). *In situ* hydraulic tests are difficult in heterogeneous fault zones because of problems with separating the test intervals, difficulties of *in situ* testing the narrow fault cores, and interpreting the results (Karasaki *et al.* 2008). In hydrogeological studies, at depths <1 km below the top of the crystalline rock at research sites a large proportion of brittle faults are seen as conduits (e.g., Stevenson *et al.* 1996; Bossart *et al.* 2001; Stober & Bucher 2007; Geier *et al.* 2012), although some of the drillhole data may not be representative of the faults tested because of heterogeneity and channeling of fracture networks. Increasing the number of drillholes does help, such as at dam foundation investigations utilizing pre-grouting injection tests (Kawagoe & Osada 2005; Barani *et al.* 2014), except that at shallow depths the fault rocks and fractures related to damage zones exist in a protolith that has been subject to weathering and decompression fracturing as a whole rock mass, including pre-existing fault zones, down to some depth. The conduit effects of faults may only appear after geostatistical analysis (Nakaya *et al.*

Table 6 Summary of proportions (%) of fault conduits relative to the total number of major fault zones crossed in tunnels and drilled at research sites.

Tunnel name and location	Conduit (%)	Depth, m (avg., max)	Lithology	Method	References
Tunnels mainly in gneiss and granite					
Gothard, Switzerland	70–76%	1200 (2000)	GN	# Fault zones with hydraulic conductivity > rock mass mean (6×10^{-9} m sec^{-1}), suggesting a conduit	Masset & Loew (2013)
23 tunnels, Switzerland	Majority	800–1000	GN	Statistical study: majority of inflow points from brittle overprint of existing brittle–ductile faults	Lutzenkirchen (2002); Masset & Loew (2010)
Mt. Blanc, France	>45%	1500 (2500)	G, S	>9 of 20 fracture groups had inflows	Maréchal (1998)
Ena (Enasan), Japan	35–85%	500 (1000)	G, V, GN	%86 inflows in 22 fault zones (37% > 1 m^3 min^{-1})	Yano *et al.* (1978)
Aica-Mules, Austria	50–100%	800 (1200)	G, M	approximately 100% faults with water inflow, approximately 50% large inflow	Perello *et al.* (2014)
Manapouri, New Zealand	approximately 80%	700 (1200)	G, M	approximately 9 of 11 fault zone groups	Upton & Sutherland (2014)
Višňové, Slovakia	65–75%	400 (600)	G, S	'Significant' inflows were at 7 of 9 major faults (>25 smaller faults had 16 inflows)	Ondrášik *et al.* (2015)
Cleuson-Dixence D, Switzerland	40%	250 (500)	GN, M-S, S	Reports of grouting or inflow at 2 of 5 faults crossed; most were dry and clay-filled	Buergi (1999)
Arrowhead E., USA	90–95%	200 (335)	G, GN	approximately 18 of 19 fault zones crossed had inflows and required grouting; impacts on springs and wells	Bearmar (2012)
H.D.Roberts (E part), USA	90%	210 (300)	GN	approximately 12 fault zones with inflows, groups of faults	Wahlstrom & Hornback (1962)
Rokko, and Hokuriku Japan	60–65%	150 (400)	G, VB	Rokko: inflow from 3 of 5 faults (postearthquake); Hokuriku: 65% fault zones with inflow >1 m^3 min^{-1}	Takahashi (1965); Yoshikawa & Asakura (1981); Asakura *et al.* (1998); Masuda & Oishi (2000)
Tseung Kwan O Bay E, Hong Kong	40–50%	120 (200)	G	approximately 2 of 5 major fault zones with large inflows, approximately 8 of 17 individual faults	GovHK (2007)
Taining, China	>70%	approximately 150 (500)	G	>5 of 7 fault and fracture zones had high inflows	Zhang *et al.* (2014)
Romeriksporten, Norway	<60%	100 (200)	GN-G	8 of 10 leakages near faults in Lutvann (lake) area; whole tunnel 4–8 of 13 weakness zones with water	Holmøy (2008); Holmøy & Nilsen (2014)
Frøya, Norway	50–65%	100 (120) subsea	GN-G	6 of 12 fault zones with inflows, 7 of 12 nonconducting faults in subsea section 4000–5600	Holmøy (2008); Holmøy & Nilsen (2014)
Storsand, Norway	30%	125 (160)	GN-G	2 of 5 leakage zones in predrilling near faults	Holmøy (2008); Holmøy & Nilsen (2014)
Hvaler, Norway	30–60%	75 (120) subsea	GN, G	approximately 5 of 13 clusters of inflow points (16 pretunneling study found 16 fault zones	Banks *et al.* (1992, 1994)
MWRA, USA	50–70%	70	M-S, G, VB	19 inflow zones correspond with 13 mapped lineament zones (68%), others do not	Mabee *et al.* (2002)
Namtall, Sweden	50%	25 to 150	M-S, G	approximately 5 of 10 fault zones with inflow, Lugeon tests	Stille & Gustafson (2010)
Tunnels mainly in sedimentary and volcanic rocks					
Lotschberg, Switzerland	50%	600–1000	S(L)	Brittle faults 50% inflows within the limestones	Passendorfer & Loew (2010)
Gran Sasso, Italy	40–50%	800 (1300)	S(L)	approximately 4 of 9 faults along tunnel show inflows; major inflows from 2 fault zones (4 faults)	Boutitie & Lunardi (1975); Lunardi (1982); Celico *et al.* (2005)
Hida, Japan	45%	750 (1000)	VS, VB, GN	3 of 7 major fault zones with inflows	Abe *et al.* (2002); Terada *et al.* (2008)
la Línea, Colombia	40–55%	500 (800)	S, VS, VB, G	approximately 13 of 23 faults are near inflow points	Suescun Casallas (2015)
Syuehshan & Ping Lin, Taiwan	<85%	400 (700)	S	5 of 6 major normal faults were associated with poor tunneling conditions and water inflows	Tseng *et al.* (2001); Chiu & Chia (2012)
Vaglia-Firenzuola-Raticosa, Italy	60–100%	300 (500)	S	Tunnel inflows and isotope study (approximately 13 of 22 fault clusters had inflows), impacts on springs & wells	Vincenzi *et al.* (2014); Ranfagni *et al.* (2015)
Harold D. Roberts (W. part), USA	50%	150 (300)	S	approximately 9 of 19 fault zones had inflows (counting groups of faults on cross sections)	Wahlstrom & Hornback (1962)

Table 6. (Continued)

Tunnel name and location	Conduit (%)	Depth, m (avg., max)	Lithology	Method	References
Lunner, and Skaugum, Norway	20–35%	100 (230)	S, VS, VD	Lunner: 2 of 6 fault zones had inflows; Skaugum: inflows mostly at lithological contacts, igneous dikes (1 of 5 'weakness zones' had large inflow)	Holmøy (2008); Holmøy & Nilsen (2014)
Karahnjukar, Iceland	>40%	200	VB	2 of 5 faults with water inflow	Kroyer *et al.* (2007)
Seikan, Japan	45%	100	S, VB, VS	4 of 9 major fault zones (>5 $m^3\ min^{-1}$ inflow)	Hashlmoto & Tanabe (1986)
Tseung Kwan O Bay C, Hong Kong	70%	50	S	7 of 10 fault zones had water inflow contributions	McLearie *et al.* (2001); GovHK (2007)
Tuzla, and Bolu, Turkey	25–45%	<100 (200)	S, G	Tuzla: 7 of 15 had 'excessive water inflow', Bolu: 3 of approximately 12 had inflow (1 of 3 thrust structures)	Dalgic (2002, 2003)
Research sites in gneiss rocks					
Nagra 6 scientific drillholes, Switzerland	approximately 45%	100–1600	GN	Faults are dominant permeable elements (43%); note: depth below top of crystalline rock	Thury *et al.* (1994); Mazurek (1998); Mazurek *et al.* (2000)
Gideå, and Fjällveden, Sweden	30–45%	200 (600)	GN	2 of 7 at Gidea, 4 of 9 at Fjällveden	Ahlbom *et al.* (1983, 1991)
Äspö, Sweden	60%	400 (1000)	GN	# Permeable major water conductive features	Ahlbom & Smelie (1991); Bossart *et al.* (2001)
Forsmark site and tunnel, Sweden	75%	400 (900)	GN	65 flowing zones of 85 in boreholes (48 different deformation zones); in tunnel 4 of 4 with inflow	Carlsson & Christianson (2007); Follin & Stigsson (2014)

Lithology listed in order of % occurrence in tunnel: G, granitic; GN, gneiss; S, sedimentary; S-L, limestone; M-S, metasedimentary; VS, volcanic sediments, tuffs; VB, basalt, andesite; VD, intrusive dikes.

2002). In large underground mines, counting the fault conduits over areas of a few square kilometers is also problematic. Recent statistical studies of large underground mines in Germany suggest a complex relationship of permeability of fault cores and damage zones at intersecting faults in three-dimensional space (Achtziger-Zupancic *et al.* 2015; P. Achtziger-Zupancic, personal communication) and is best shown statistically. In such cases, it is not clear how to count the fault conduits and barriers. Is there an average permeability structure of a large site containing many faults? And, at what scale do the fault zones need to be tested and counted to provide useful representative hydraulic properties for site and regional models?

The proportion of barrier fault zones is more uncertain in this study than of the conduits because barriers are more difficult to detect with hydraulic tests. For large-scale characterization, observing the 'barrier' nature of fault zones requires completely different methods than those for 'conduits'. In hydrogeological studies, groundwater aquifer compartmentalization is common in faulted sedimentary rocks (e.g., Mohamed & Worden 2006; Bense *et al.* 2013) and in crystalline rocks (e.g., Benedek *et al.* 2009; Takeuchi *et al.* 2013). While the presence of compartmentalization can be detected through cross-fault tests or observations of natural hydraulic or thermal gradients (Bense *et al.* 2013), typical hydraulic tests in boreholes rely heavily on interpretation of distant fault flow boundaries (e.g., Stober & Bucher 2007). The barrier effect is easily seen in some cases of large excavations around dams (Li & Han 2004) and open-pit mines (McKelvey *et al.* 2002). It has been known for decades in tunnel engineering that during tunnel excavation, the barrier–conduit nature of faults may be recognized when a fault gouge 'membrane' is penetrated when tunneling from the low-pressure side of a barrier, and sudden inflow to tunnel occurs (Henderson 1939; Brekke & Howard 1972; Fujita *et al.* 1978). In the large number of papers and reports reviewed, the majority of the cases described in geotechnical and engineering papers describe geotechnical instabilities of faults rather than water problems, although in some cases those occur at the same place. Therefore, we can qualitatively infer that there may exist a large proportion of barrier faults in the crust that are not counted in this study as barriers.

Estimating the proportion of faults that are conduits

The proportion of fault zones that are permeable conduits to groundwater flow was estimated using two methods: counts of fault conduits at study sites (proportion is relative to total number of sites considered) and counts of fault conduits along long tunnels (the proportion is relative to the total number of major fault zones crossed in a tunnel).

From tunneling data in the crystalline rocks, the proportion of fault conduits varies from about 40% to more than 90%, with a median proportion of about 60% (Fig. 6A). The large research sites where multiple faults were drilled

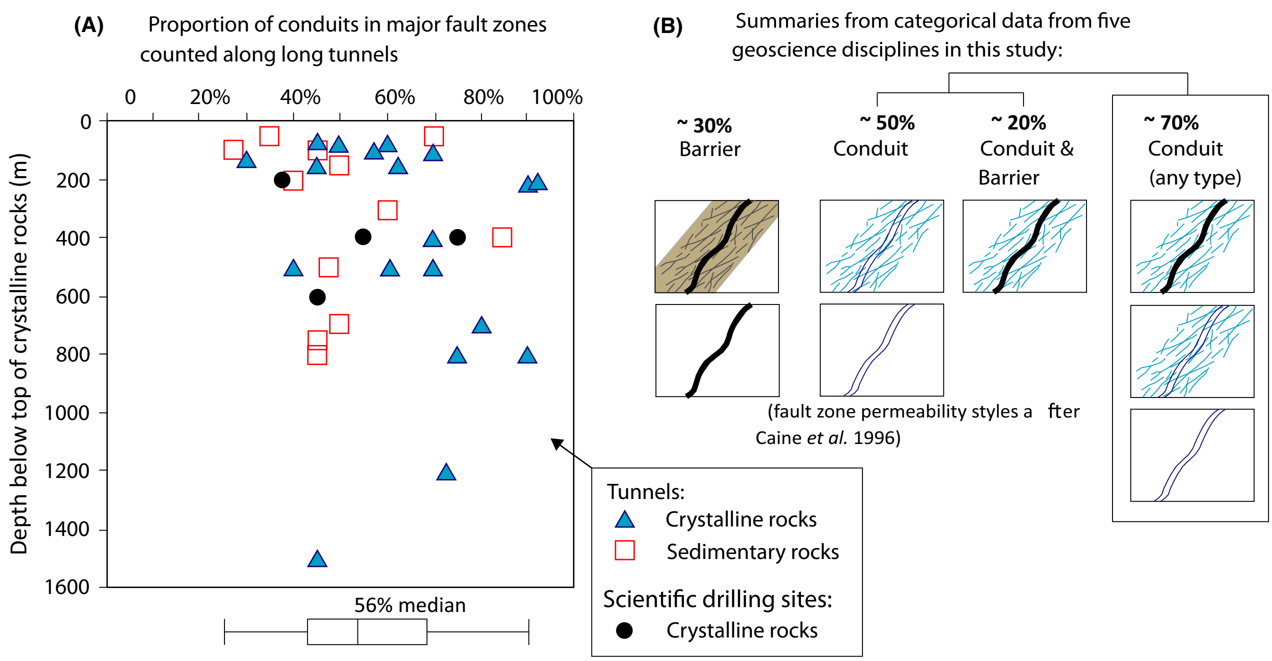

Fig. 6. Global proportions and trends with depth of conduits in major fault zones (A) counted along long tunnels and representing several large research sites (Table 6 data summary), and, (B) estimates based on the global database of fault zone study sites from five geoscience disciplines (Table 1) and graphical description of fault zone permeability structural styles (Caine *et al.* 1996) included in our simplified categories.

and tested were also added to this plot to compare to the tunnel data. At the four research sites the proportion of conductive faults is between 40% and 75%. With this limited number of case studies and counts of faults, it is not clear yet whether a depth trend exists in the crystalline rocks of increasing proportion of fault conduits, although this may be an interesting topic of research.

From the global counts of whole 'sites' in the five geoscience disciplines, we estimate that there are 70% fault conduits of any type. Figure 6B shows graphically that our simple categories may contain a range of different fault zone architectural styles as defined in Caine *et al.* 1996, and this study aggregates all types of conduits and all types of barriers, as long as that hydraulic behavior is observed. In tunnels, water inflow will occur whether a fault is a 'conduit only' or a 'barrier–conduit', as long as it is a conduit that is permeable in comparison to the protolith; therefore, the tunnel and global site data are comparable.

There are limitations and uncertainties in the tunnel data. Tunnels are grouted during construction to control in permeable zones to control the groundwater inflows; thus, the inflow rates after completion may be much smaller than during construction. However, grout volumes have been shown to correlate with individual fault permeability structures (Ganerød *et al.* 2008) and reports of tunnels inflows and grouting are also correlated at most studies we reviewed. The weathering of fault zones may occur to depths greater than 100 m and effectively seal the fault with clays. For example, in northern Europe, the faults are affected by paleo-weathering (Migoń & Lidmar-Bergström 2001) and this is thought to cause a reduction of fault permeability to such an extent that the fault conduit may not exist or may not be noticed during tunneling, for example in fjord-crossing subsea tunnels in Norway (Holmøy & Nilsen 2014, Nilsen 2012). Inflow rates are also controlled by boundary conditions and type of surficial materials (Cesano *et al.* 2000) and the depth of tunnel below the water table. 'Dry' faults may still be conduits but not be noticed during tunneling. Inflows may be erroneously attributed to fault zones in the crystalline rocks because about 50% of permeable conduits are reported by various authors to be outside of fault zones (Masset & Loew 2010, 2013; Nilsen 2012). These can include intrusive dikes and other permeable elements (Thury *et al.* 1994, Font-Capo *et al.* 2012; Mayer *et al.* 2014). Our estimate is that the conduit proportions for each tunnel could be 10% higher or lower on the scale plotted in Fig. 6A. Despite these limitations, these quantities provide useful insight into the hydrogeology of fault zones, although in a highly simplified presentation.

DATA AVAILABILITY

The database containing the fault zone attributes used in this study is available in the supplementary information associated with this article as well as through online portals such as figshare and the Crustal Permeability Data Portal.

ACKNOWLEDGEMENTS

We thank Dr. Andreas Hartmann for useful suggestions that clarified the presentation of statistical methods, Peter Achtziger-Zupancic and Simon Loew for past discussions about faults in tunnels and mines, JAEA hydrogeologists at Mizunami for explaining the fault permeability structure there, and Jonathan Caine at the USGS for helpful comments on these results. Funding for the research is provided by *Fonds de Recherche du Québec – Nature et technologies* (FRQNT).

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SUPPORTING INFORMATION

Additional Supporting Information may be found online in the supporting information tab for this article:

Table S1. Listing of categorical data of fault zone hydrogeology conceptual models.

Table S2. Observation method counts by categories of fault zone permeability structure and geoscience discipline.

Table S3. Observation method categories combined or removed (if not enough counts).

GEOFLUIDS

Volume 16, Number 4, November 2016
ISSN 1468-8115

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WILEY Blackwell

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