

Research papers

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Yunmei Fu, Yanhui Dong, Liheng Wang, Olivier Bour, Maria V. Klepikova, Zihua Zong, Zhifang Xu, Zhichao Zhou

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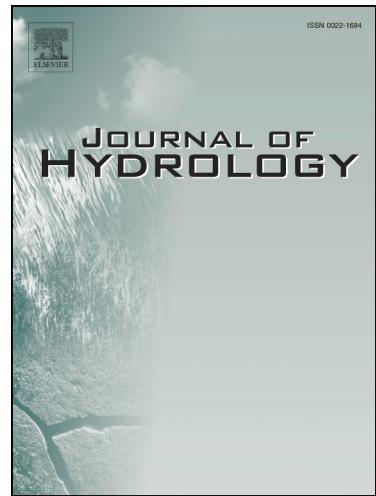
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1 **Characteristics of hydraulic conductivity in mountain block systems and its effects**
2 **on mountain block recharge: Insights from field investigation and numerical**
3 **modeling**

4 Yunmei Fu^{a,b,c}, Yanhui Dong^{a,b,c,*}, Liheng Wang^{a,b,c}, Olivier Bour^d, Maria V.
5 Klepikova^d, Zihua Zong^{e,f}, Zhifang Xu^{a,b,c}, Zhichao Zhou^{e,f}

6 ^a Key laboratory of Shale Gas and Geoengineering, Institute of Geology and
7 Geophysics, Chinese Academy of Sciences, Beijing 100029, China

8 ^b Innovation Academy for Earth Science, Chinese Academy of Science, Beijing 100029,
9 China

10 ^c College of Earth and Planetary Science, University of Chinese Academy of Sciences,
11 Beijing 100049, China

12 ^d Univ Rennes, CNRS, Géosciences Rennes, UMR 6118, 35000 Rennes, France

13 ^e Beijing Research Institute of Uranium Geology, Beijing 100029, China

HLW: High-level radioactive waste; MBR: Mountain block recharge; MFR: Mountain-front recharge;
STEP: Scientific Expedition and Research Program; TDS: Total dissolved solid; URL: Underground
research laboratory; IQR: interquartile range

14 ^f CAEA Innovation Center for Geological Disposal of High-level Radioactive Waste,

15 Beijing 100029, China

16 *Corresponding Author;

17 Yanhui Dong

18 Key laboratory of Shale Gas and Geoengineering, Institute of Geology and Geophysics,

19 Chinese Academy of Sciences, Beijing 100029, China

20 Phone: +86 13910954926

21 Fax: +86 10 82998617

22 Email: dongyh@mail.igcas.ac.cn

23 **Abstract**

24 The process wherein groundwater flowing from mountain bedrock into lowland and

25 adjacent alluvial aquifers, known as mountain-block recharge (MBR), is found across

26 various climatic and geological settings. An understanding of the potential groundwater

27 flow paths in mountain block systems is necessary for comprehending MBR spatial

28 distribution. However, poorly characterized mountain block hydraulic properties, and

29 especially a lack of direct measurements of hydraulic conductivity (K) at depths >200

30 m, limit the characterization and quantifications of the MBR processes. In this study,
31 we analyze hydraulic data set, namely 555 in-situ K measurements at various depths
32 from two borehole sections extending from mountain block to mountain front in a
33 potential disposal site for high-level radioactive waste. The K dataset was categorized
34 into two groups: one for bedrock and another for fault zones, which was further
35 classified into fault core K , damage zone K , and general fault zone K . Using a
36 permeability conceptual model and multiple scenarios numerical modelling, this study
37 examined the potential flow paths of MBR processes, mainly focusing on the
38 characteristics of K in bedrocks and the hydraulic role of fault zones in mountain block
39 systems. The distribution of Bedrock K supports the assumption of decreased trend with
40 depth. A logarithmic fit through Bedrock K and depth pairs resulted in $\text{Log}(K) = -$
41 $1.62 * \text{Log}(z) - 6.52$, with low predictive power. This study illustrated the localized
42 effects and spatially variable roles of fault zones in MBR within this particular
43 hydrogeological configuration in Beishan, China. Our results provide insights into the
44 MBR process in crystalline mountain block systems. Additionally, the hydraulic
45 conductivity presented here provides data on the subsurface properties of mountain
46 block systems in a crystalline area, and further facilitates the characterization and
47 quantification of mountain-block recharge.

48 **Keywords:** mountain block recharge, mountain hydrogeology, fractured aquifer

49

50 **1 Introduction**

51 Mountainous areas play an important role in the global water cycle and constitute the
52 water source for numerous populated regions at lower elevations (Jódar et al., 2017;
53 Lone et al., 2021; Somers and McKenzie, 2020; Vivioli et al., 2020; Wilson and Guan,
54 2004). Water from mountainous areas recharges lowlands via mountain-front recharge
55 (MFR) and mountain-block recharge (MBR; (Aishlin and McNamara, 2011; Ajami et
56 al., 2011; Bresciani et al., 2018; Manning and Solomon, 2003; Markovich et al., 2019;
57 Peng et al., 2018; Taucare et al., 2020; Wilson and Guan, 2004). MFR refers to the
58 focused and net infiltration from perennial and ephemeral streams originating in the
59 mountain block, which occurs at the piedmont zone (Markovich et al., 2019; Wilson
60 and Guan, 2004). MBR refers to the groundwater flow from the mountain block into an
61 adjacent alluvial aquifer, and is also referred to as “inter-aquifer recharge” (Healy, 2010)
62 or “subsurface inflow” (Manning and Solomon, 2003). MBR may recharge adjacent
63 aquifers by two processes: diffuse MBR and focused MBR (Wilson and Guan, 2004).
64 Diffuse MBR occurs widely within mountain blocks, including the mountain front area
65 (Markovich et al., 2019; Wilson and Guan, 2004). Focused MBR corresponds to
66 groundwater flow through permeable colluvium-alluvium corridors in gullies or
67 canyons joining the adjacent basin, and oblique basement faults crossing the mountain

68 front area, which may promote groundwater flow into the adjacent basin (Figueroa et
69 al., 2021; Markovich et al., 2019; Wilson and Guan, 2004).

70 Previous studies have largely focused on understanding the fundamental factors
71 determining the location and extent of MBR, with the hydraulic conductivity (K)
72 distribution within mountain bedrock and the role that fault zones play being two vital
73 factors (Gleeson and Manning, 2008; Markovich et al., 2019; Welch et al., 2012;
74 Wilson and Guan, 2004). K distribution was identified as one of the first-order controls
75 of the rate and distribution of MBR (Forster and Smith, 1988; Gleeson and Manning,
76 2008; Haitjema and Mitchell-Bruker, 2005; Markovich et al., 2019; Welch et al., 2012;
77 Wilson and Guan, 2004). The general conceptual model for mountain groundwater flow
78 systems is composed of a higher- K “active” zone (the aquifer) that overlies a deep low-
79 K zone (relatively impermeable bedrock) (Manning and Caine, 2007; Markovich et al.,
80 2019; Welch et al., 2012). The existence of an “active” zone with $K > 10^{-8} \text{ m}^{-1}$ where
81 active mountain groundwater flow can be produced, and a recharge rate greater than
82 roughly 10 mm/year are prerequisites for the occurrence of MBR (Markovich et al.,
83 2019). If some MBR exists, major faults near the mountain front can potentially either
84 impede or enhance MBR. Theoretically, major faults oriented at a high angle to the
85 MBR flow paths might act as barriers to MBR as the groundwater must flow across the
86 fault zone to enter the adjacent aquifers (Chowdhury et al., 2008; Delinom, 2009;

87 Figueroa et al., 2021; Kebede et al., 2008). In contrast, obliquely oriented faults (more
88 parallel to MBR flow paths) within the bedrock could act as conduits for groundwater
89 flow and promote MBR (Figueroa et al., 2021). However, the results from field
90 examination, hydrochemical, and groundwater age assessment provide evidence that
91 the orientations of faults do not determine their role in mountain block hydrogeological
92 processes (Caine et al., 2017; Kebede et al., 2008), and the oblique oriented faults could
93 act as barriers to MBR. Therefore, the possible permeability structure and the actual
94 hydraulic influence of mountain-block faults in MBR processes (impeding or
95 enhancing) remain speculative.

96 Although the vital controls of the MBR process have been identified, the
97 characterization and quantification of MBR processes remain challenging in mountain
98 block hydrogeology because of the intrinsic heterogeneity of K distribution and fault
99 zones and data limitation, particularly of subsurface data from the mountain block and
100 mountain front (Markovich et al., 2019; Yao et al., 2017).

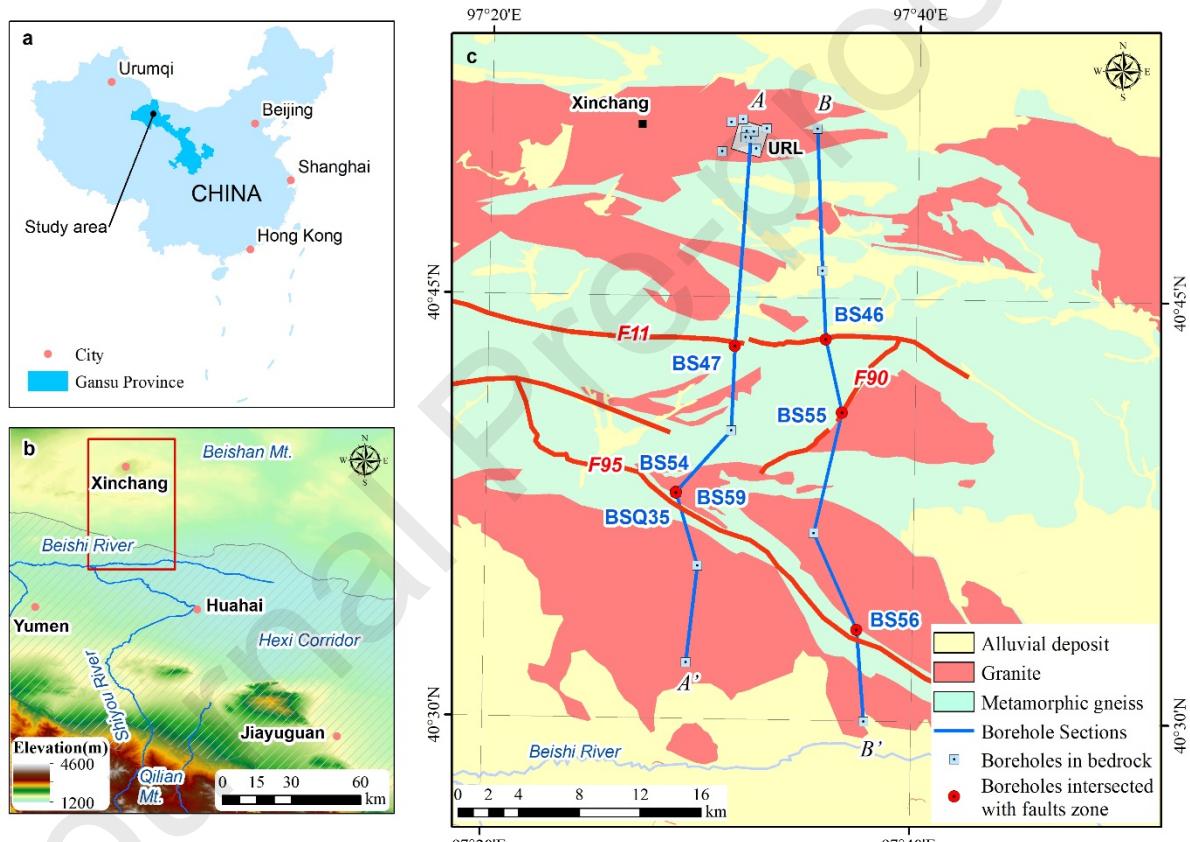
101 Several studies proposed to bypass determining actual K distribution by employing
102 synthetic or semi-synthetic subsurface K structures in models (Engdahl and Maxwell,
103 2015; Gleeson and Manning, 2008; Voeckler et al., 2014; Wang et al., 2018a; Welch et
104 al., 2012). Few studies are based on the actual K , using data sets at depths of 0–20 m
105 (Ameli et al., 2018) and 10–200 m (Welch and Allen, 2014). Most of these works have
6

106 generally converged that the typical groundwater active circulation depth for fractured
107 crystalline rock environments may extend to 200 m subsurface, with $K = 10^{-8} \text{ m}\cdot\text{s}^{-1}$
108 (Manning and Ingebritsen, 1999; Markovich et al., 2019; Rapp et al., 2020), surpassing
109 the K data depth previously used. In addition, the target depth of geo-environmental
110 systems engineering related to mountain groundwater systems is much deeper. For
111 example, the site selection for long-term nuclear waste is targeted at 300–500 m (Tóth
112 and Sheng, 1996; Voss and Provost, 2001; Wang et al., 2018b); whereas CO₂ geological
113 storage target depths are ≥ 800 m (Bickle, 2009; Gunter et al., 2004). In contrast, direct
114 subsurface measurements of K at depths > 200 m are rare (Markovich et al., 2019).
115 Therefore, studies providing access to a range of actual bedrock properties (especially
116 K) at depths > 200 m should be prioritized in mountain block system hydrogeology.

117 In this study, we report a series of in-situ measured hydraulic conductivities ($n = 555$)
118 from a crystalline mountain block system to complement hydrogeological databases at
119 depths > 200 m in mountain systems. The data set includes K measured in crystalline
120 bedrock ($n = 512$) and within fault zones ($n = 43$), ranging from 0 m to 592.3 m below
121 the ground surface (mbgs). All data were obtained from the Beishan area, Gansu
122 Province, China, a disposal site for high-level radioactive waste (HLW). Given the
123 possibility of groundwater acting as a carrier of radionuclides, understanding the flow
124 paths in MBR processes in the study area is critical for determining the safety of HLW

125 disposal. Based on a permeability conceptual model and numerical modelling built on
 126 in-situ measurements, this study explores the possible flow paths for MBR in this area,
 127 focusing on the K distribution, associated heterogeneity and the hydraulic role of fault
 128 zones.

129 **2 Study area**



130

Figure 1. a. Location of the study area, b. topography of the study area, and c. borehole sections (where field data were obtained) and geology.

131 This study was conducted in the Beishan area situated in the Gansu Province of

132 northwestern China (Fig 1a). The study area is an inland mountain range covering an
133 area of approximately 3,973.9 km² and is located north of the Huahai Basin in the Hexi
134 Corridor, where multiple cities (including Yumen, Jiayuguan, and Huahai) with more
135 than 9 million inhabitants are located. With an altitude ranging between 873 m and
136 2,556 m above sea level, the Beishan area primarily consists of low altitude mountains
137 and small hills. The Xinchang Site, which is the prospective location for China's HLW
138 repository and the location of China's first underground research laboratory (URL), is
139 located to the southwest of the Beishan area and is approximately 60 km from the
140 nearest city of Yumen (Fig 1b). The site covers an area of >100 km² with an altitude
141 ranging between 1,400 and 1,800 m (Zhou et al., 2020)

142 Metamorphic rocks (mainly Ordovician or Silurian gneiss), intrusive rocks (mainly
143 Permian granite) and sediments (mainly Quaternary clay and sandy loam weathered
144 from gneiss and granite) comprise the main lithology of the study area, with occasional
145 alluvium deposits (usually <10 m) in the ground (Peng, 2013; Wang et al., 2018b). The
146 cores obtained from the Xinchang Site are dominated by gneissic biotite monzonitic
147 granite and biotite granodiorite (Zhao et al., 2016).

148 The Beishan area is characterized by an arid climate with an annual average
149 precipitation of 73.1 mm·yr⁻¹ and a mean annual potential evaporation of >3,000 mm
150 (Zhou et al., 2020). Except for the Beishi River, a river originating from Qilian
9

151 Mountain and flows eastward passing the study area, no other perennial river is found
 152 within the area due to extreme drought, although ephemeral deluge can occur after brief
 153 precipitation events in the summer (Cao et al., 2017a; Cao et al., 2017b; Dong et al.,
 154 2009).

155

156 Several faults have been identified in the study area, including two major faults (F11
 157 and F95), and several local faults (F90). The fault kinematics and architectures, as
 158 determined by surface geological mapping and borehole drilling, are provided in Table
 159 1 (Gansu Geology Survey, 1978; Guo et al., 2003; Guo et al., 2014; Wang et al., 2018b).

160 The F11 fault is located in a metamorphic gneiss south of the Xinchang Site and is
 161 approximately perpendicular to the mountain slope. F90 is the most representative of
 162 the secondary faults of F11 and is located in granite and metamorphic gneiss (Gansu
 163 Geology Survey, 1978). The F95 fault is an NW striking fault developed in
 164 metamorphic gneiss between two intrusive granite zones and extends directly from the
 165 mountain front to the Huaihai Basin (Gansu Geology Survey, 1978; Guo et al., 2003;
 166 Guo et al., 2014; Wang et al., 2018b).

Table 1. Fault kinematics and architectures.

Section	Fault	Strike	Dip	Geology	Thickness
---------	-------	--------	-----	---------	-----------

					Total zone (m)	Fault core (m)	Damage zone (m)
				Metamorphic gneiss	-	10.6	-
A-A'	F11	W-SW	70				
				Metamorphic gneiss	64.4	30.2	34.2
	F95	NW-SE	78				
				Metamorphic gneiss	-	1.4	-
	F11	W-SW	60				
				Granite & Metamorphic gneiss	52.4	-	-
B-B'	F90	NE-SW	60				
				Metamorphic gneiss	67.0	1.6	65.4
	F95	NW-SE	75				

167 Hydrogeochemical characteristics reveal the evolution processes of groundwater by
 168 recording the interaction between groundwater and the aquifer medium. Accordingly,
 169 the hydrogeochemical data of groundwater in the Beishan area were comprehensively
 170 collected from published literature, revealing a range of pH values from 7.39 to 10.14,
 171 groundwater temperature between 8 and 17 °C, and a total dissolved solid (TDS)
 172 content of 0.7–19.0 g·L⁻¹ (Guo et al., 2014; Li, 2020; Wang et al., 2018b; Wang, 2015).
 173 In particular, high TDS was observed in shallow groundwater, indicating that the

174 groundwater underwent strong evaporation. Based on isotopic data and groundwater
175 age, previous studies have also shown that groundwater in the study area is recharged
176 primarily by local precipitation (Li, 2020). The groundwater flow is controlled by
177 topography (Dong et al., 2009; Wang, 2015).

178 **3. Methods**

179 *3.1 Hydraulic conductivity measurements, categories, and characterization*

180 3.1.1 *K* measurements and categories

181 A total of 555 hydraulic conductivity measurements were obtained from 22 boreholes
182 (Table 1). Boreholes were drilled through the surface weathering rock and into the
183 bedrock, reaching a maximum depth of 690.7 m, permitting the characterization of the
184 mountain block hydraulic conductivity. All data were obtained via in-situ tests
185 (including constant-head injection, plug, or slug tests using packer systems); therefore,
186 these data are all defined as bulk permeability instead of matrix permeability (Scibek,
187 2020; Scibek et al., 2016). The measuring intervals of in-situ tests differ from 12 to 50
188 m along the boreholes, and were also extended to 202 m to investigate the fault zones
189 intersected by the boreholes.

190 Seven of the 22 boreholes have intersected fault zones. Data from all 555 hydraulic

191 conductivity measurements were classified into two categories based on the measured
192 locations: Bedrock K , which refers to K obtained from in-situ tests conducted away
193 from any fault zones ($n = 512$, shown as blue squares in Figure 2), and K measured in
194 fault zones ($n = 43$, shown as circles in Figure 2). For K measured in fault zones, the
195 data were further divided into three categories: Core zone K , which refers to the data
196 obtained within the zone that is clearly identified as a fault core and isolated in the in-
197 situ tests ($n = 2$, shown as yellow circles in Figure 2); Damage zone K , which refers to
198 the data measured only within the fault damage zone ($n = 33$, shown as red circles in
199 Figure 2); and General fault K , which refers to the data from test intervals including
200 both fault damage zones and the main fault core zones ($n = 8$, shown as green circles in
201 Figure 2). General fault K occurred due to either of two reasons: the isolation of the
202 fault core zone or damage zone was not available for in-situ tests due to potential
203 collapsibility of boreholes, or, it was difficult to clearly identify the damage and fault
204 core zones within a fault zone.

205 The Bedrock K data ($n = 512$, shown as blue squares in Figure 2a) was divided into
206 measurement depth intervals of 50 m, and the arithmetic mean, median, 10% and 90%
207 confidence distribution of each interval were calculated. A linear regression of log
208 hydraulic conductivity (log K) over log depth (log z) was performed on the Bedrock K
209 data, considering the previous understanding that K decays exponentially with an

210 increase in depth (Achtziger-Zupančič et al., 2017).

211 3.1.2 Characterization of permeability structure

212 A vertical layer profile of the study area was created based on the data. Instead of
213 adapting detailed definitions and descriptions of weathering and fracture, the vertical
214 distribution of K and its relative differences established the primary principles for
215 constructing a conceptualized model of the mountain block systems.

216 From a hydrogeological perspective, a domain can be viewed as a pervious formation
217 with $K \geq 1.00 \text{ E-}8 \text{ m}\cdot\text{s}^{-1}$, where active groundwater flow may be produced (Katsura et
218 al., 2009; Markovich et al., 2019; Welch and Allen, 2014). Therefore, a threshold value
219 of $K_0 = 1.00 \text{ E-}8 \text{ m}\cdot\text{s}^{-1}$ was adapted to indicating K 's relative difference by depth in
220 bedrock. The probability $K > K_0$ (P) and the arithmetic mean K value of every 50 m
221 depth were calculated. Based on the calculated results and the vertical conceptual model
222 for fractured crystalline-rock mountain block system of Welch and Allen (2014), the
223 vertical permeability structure of the mountain block in the study area was then divided
224 into three layers: the Weathered Zone (including soil and highly weathered rock), the
225 Fractured Zone, and the Inactive Zone (relatively impermeable bedrock with majority
226 of $K < K_0$, where active groundwater may not be produced).

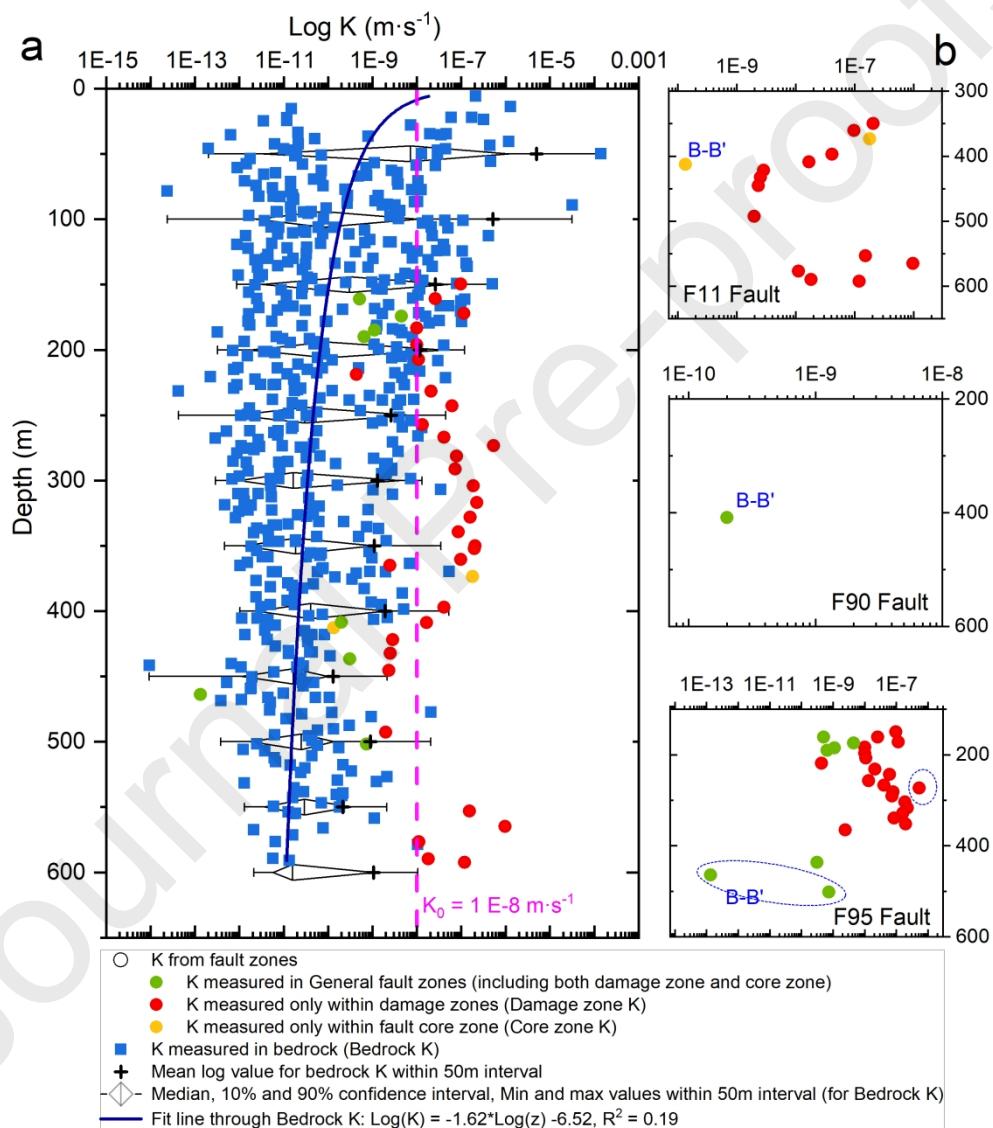
227 The permeability ratios (Scibek, 2020) can be used to quantify the “conduit” or “barrier”

228 magnitudes of a fault zone using the permeability of the general fault zone (or fault core)
 229 and host rock obtained at specific locations (ideally along the same drillhole or outcrop
 230 section). In this study, permeability (m^2) was replaced with hydraulic conductivity ($\text{m}\cdot\text{s}^{-1}$
 231¹⁾ in the calculation for data consistency, and therefore refers to this ratio as hydraulic
 232 conductivity ratio (K ratio).

$$233 \quad K \text{ ratio} = \log_{10} \frac{K_{\text{General fault zone/ Core}}}{K_{\text{Host rock}}}$$

234 *3.2 Groundwater flow analysis– numerical modelling*

235 To investigate the flow behavior of faults in the study area, a 2D hydrogeological
 236 numerical model coupled with particle tracking was applied. MODFLOW-USG was
 237 used to simulate the hydrogeological processes of mountain blocks, and Darcy's Law
 238 Module was used to describe groundwater flow. We constrained the model based on
 239 the topographical section B-B', as well as the hydraulic properties described in Section
 240 4.

241 **4. Results**242 *4.1 Characteristics of hydraulic conductivity*243 *4.1.1 Hydraulic conductivity of bedrock*

244

Figure 2. Distribution of hydraulic conductivity (K) with depth, a. Depth trend of K for bedrock (n = 512, shown as blue squares) and fault zones (n = 43, shown as circles) derived from in-situ hydraulic testing in 22 boreholes; b. K from three faults, i.e., F11 fault, F90 fault and F95 fault.

245 Figure 2a shows K distribution with depth in the study area, including Bedrock K (n =
 246 512) and K from fault zones (n = 43). Both the highest hydraulic conductivity (1.40 E-
 247 4 m·s⁻¹ at 50.0 m depth) and lowest hydraulic conductivity (9.39 E-15 m·s⁻¹ at 441.5 m
 248 depth) were observed in Bedrock K. Only two of the 555 K data are greater than 1.00
 249 E-5 m·s⁻¹, both within the depth less than 100.0 m. The hydraulic conductivity data is
 250 shown to be more scattered at shallow depths than at deeper ones, and shows substantial
 251 variance near the surface.

252 A logarithmic fit through Bedrock K and depth pairs resulted in $\text{Log}(K)$
 253 = $-1.62 * \text{Log}(z) - 6.52$, with low predictive power ($R^2 = 0.19$). The slope of the
 254 regression reveals that the hydraulic conductivity averages 1.62 orders of magnitude
 255 per order of magnitude of depth change.

256 4.1.2 Fault zone hydraulic conductivity

257 Figure 2b shows 43 K measured in fault zones (2 Core zone K, 33 Damage zone K, and
 258 8 General fault zone K), revealing the permeability of three faults: F90, F95 and F11.

259 For F11, two Core zone K were measured in boreholes at different locations that showed
 260 a large variance: $1.80 \text{ E-}7 \text{ m}\cdot\text{s}^{-1}$ in the western part (A-A'), and $1.34 \text{ E-}10 \text{ m}\cdot\text{s}^{-1}$ in the
 261 eastern part (B-B'). All Damage zone K of F11 were obtained from the same borehole
 262 located in the western part (A-A') and are distributed within 2 orders of magnitudes
 263 ($1.97 \text{ E-}9 \text{ m}\cdot\text{s}^{-1} - 9.71 \text{ E-}7 \text{ m}\cdot\text{s}^{-1}$).

264 The overall hydraulic conductivity of F90 (including fault core and damage zone) was
 265 low permeable with a General fault zone K of $2.00 \text{ E-}10 \text{ m}\cdot\text{s}^{-1}$. For F95, General fault
 266 zone K obtained from the western part (B-B') ranged from $1.33 \text{ E-}13 \text{ m}\cdot\text{s}^{-1}$ to 7.31 E-
 267 $10 \text{ m}\cdot\text{s}^{-1}$, with the ones from the western part (A-A') showing a larger variance. Damage
 268 zone K were all centralized between $4.31 \text{ E-}10 \text{ m}\cdot\text{s}^{-1}$ and $5.35 \text{ E-}7 \text{ m}\cdot\text{s}^{-1}$.

269 *4.2 Mountain-basin conceptual model*

270 *4.2.1 Bedrock permeability structure*

271 Based on the calculated results and the vertical conceptual model for fractured
 272 crystalline-rock mountain block system of Welch and Allen (2014), the vertical
 273 permeability structure of the mountain block in the study area can be classified into
 274 three layers: 0–50 mbgs for the Weathered Zone (including soil and highly weathered
 275 rock), 50–350 mbgs for the Fractured Zone, and >350 mbgs for the Inactive Zone
 276 (relatively impermeable bedrock with majority of $K < K_0$).

277 The arithmetic mean value of K was $4.80 \text{ E-}6 \text{ m}\cdot\text{s}^{-1}$, $1.01 \text{ E-}7 \text{ m}\cdot\text{s}^{-1}$, and $9.08 \text{ E-}10 \text{ m}\cdot\text{s}^{-1}$
 278 for the Weathered Zone, Fractured Zone, and Inactive Zone respectively. The
 279 proportion of $K \geq K_0$ was 48.28% within the Weathered Zone, whereas it decreased to
 280 13.22% within the Fractured zone and to 2.24% within the Inactive Zone (350–600 m).

281 To better reveal the hydraulic properties of each layer, the interquartile range (IQR)
 282 measure of statistical dispersion was used to remove extreme K values in each layer.
 283 Subsequently, the arithmetic mean K values of the three layers were recalculated as
 284 $1.16 \text{ E-}8 \text{ m}\cdot\text{s}^{-1}$ for the Weathered Zone, $5.69 \text{ E-}9 \text{ m}\cdot\text{s}^{-1}$ for the Fractured Zone, and 9.08
 285 $\text{E-}10 \text{ m}\cdot\text{s}^{-1}$ for the Inactive Zone.

286 4.2.2 Permeability structure of faults

287 Table 3 lists the calculated K ratios of faults, indicating their potential permeability
 288 structures in the study area. The K ratio of F11 in the western part (A-A') was 2.64,
 289 which indicates a potential conduit for groundwater; however, the ratio in the eastern
 290 part (B-B') was -1.81, which suggests a potential barrier for groundwater. This
 291 inconsistency in hydraulic properties implies possible spatial variability in permeability
 292 structure for the same fault.

293 In contrast to F11, F95 shows consistency in K ratios: -0.75 and -0.53 for the western
 294 part (A-A') and the eastern part (B-B') respectively, indicating that F95 may impede

295 groundwater flow and acts as a “barrier”. K ratio of -0.96 for F90 also suggests a
 296 potential “barrier” for groundwater flow.

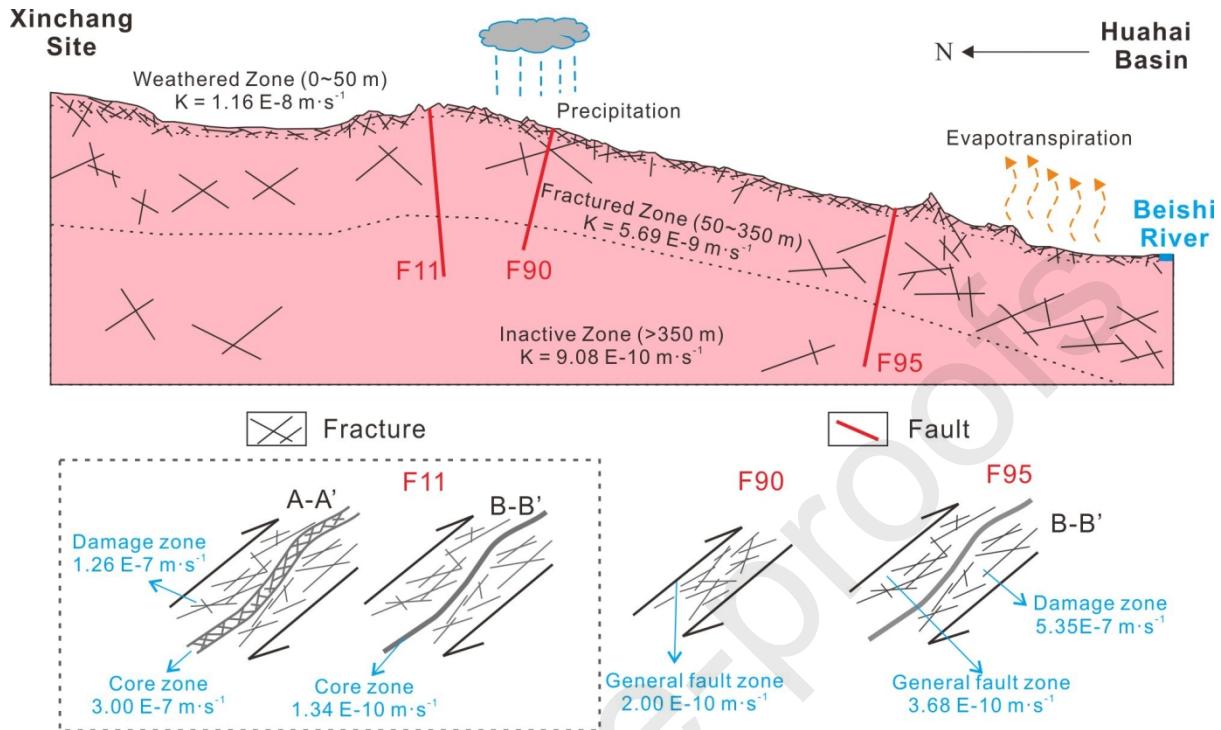
*Table 2 Fault information and calculated K ratios (*represented averaged values)*

Section	Fault	General fault zone K	Core zone K	Host rock K	K ratio
A-A'	F11	-	3.00E-7	4.15E-10*	2.86
	F95	1.41E-9*	-	7.89E-9*	-0.75
B-B'	F11	-	1.34E-10	8.74E-9*	-1.81
	F90	2.00E-10	-	1.84E-9*	-0.96
	F95	3.68E-10*	-	1.25E-9*	-0.53

297 4.2.3 Conceptual model

298 A conceptual hydrogeological model of the study area is shown in Figure 3. Based on
 299 the permeability structures of bedrock and faults, the 2D conceptual model was
 300 vertically divided into three layers. The arithmetic mean K values with extreme values
 301 removed by the interquartile range (IQR) method were selected to represent each zone.
 302 Three faults (F11, F90, and F95) were considered in this conceptual model. The
 303 hydraulic conductivity of F95 and F90 were labelled according to the information
 304 obtained on the eastern part (B-B'). However, their hydraulic impact remains the
 305 primary source of uncertainty in this conceptual model for characterizing groundwater
 306 flow patterns in the study area.

307



308

Fig 3. Conceptual hydrogeological model of the study area, and the permeability structures of faults (A-A', B-B' representing the sections where hydraulic conductivity was measured).

309 4.3 Groundwater flow patterns in study area – numerical model results

310 4.3.1 Model scenarios and setup

311 The following four field scenarios were developed based on the permeability
 312 conceptual model built in Section 4.2: homogeneous permeability, layered permeability,
 313 layered permeability with low permeable core zone of F11, and layered permeability

314 with high permeable core zone of F11. All scenarios were simulated in steady state flow,
 315 with Scenarios 3 and 4 designed to investigate the potential hydrogeological role of F11,
 316 F90, and F95 faults. The scenario details are as follows:

317 *Homogeneous* scenario: Served as the baseline model, where an arithmetic mean K
 318 value of the weathered zone calculated in Section 4.1 ($1.16 \text{ E-}8 \text{ m}\cdot\text{s}^{-1}$) was applied
 319 to represent the general hydraulic conductivity. This approach maintained a
 320 constant hydraulic property of the model domain, allowing the results to reflect a
 321 direct control of topography on groundwater flow patterns within the study area.

322 *Layered: without faults* (Layered permeability field) scenario: Here, the
 323 permeability was consistent with the conceptual model in Section 4.2.3, except for
 324 the faults. This scenario did not include faults, an appropriate assumption when
 325 controlling for the vertical distribution of K along the hydrogeological conditions
 326 of mountain blocks.

327 *Layered: low K fault* (Layered permeability field scenario with low permeable core
 328 zone of F11) scenario: Building upon the former scenario, but considering three
 329 faults (F11, F90, and F95). F11 and F95 were conceptualized as damage zones and
 330 fault cores. The measurements of the western part (B-B') of F95 were used to
 331 represent this fault: an average of General Fault zones K ($3.68 \text{ E-}10 \text{ m}\cdot\text{s}^{-1}$) was
 332 assigned to the core zone (as no measurement was available within the F95 fault

333 core); the measured Damage zone K ($5.35 \text{ E-}7 \text{ m}\cdot\text{s}^{-1}$) was used for damage zone.

334 For F11, the lower measured value of $1.34 \text{ E-}10 \text{ m}\cdot\text{s}^{-1}$ was selected to represent the

335 permeability of F11 fault core (Figure 3), and the damage zone hydraulic

336 conductivity was $1.26 \text{ E-}7 \text{ m}\cdot\text{s}^{-1}$.

337 *Layered: high K fault* (Layered permeability field with a highly permeable core

338 zone of F11) scenario: Building upon the former scenario, but replacing the K value

339 of F11 fault core zone with $3.00 \text{ E-}7 \text{ m}\cdot\text{s}^{-1}$.

340 The upper boundary of this model was conceptualized as a constant-head boundary to

341 reflect the high correlation between hydraulic head and topography within the study

342 area. At this boundary point, the groundwater head was identical to the ground elevation.

343 The Beishi River, located at the foot of the mountain bedrock, was also regarded as a

344 constant-head boundary; whereas the lateral and lower boundaries were specified as

345 no-flow boundaries. Precipitation and evaporation were not considered in the model.

346 While the study area has a typical arid climate (low precipitation, high evaporation),

347 this assumption is appropriate as the model simulates the general topography and

348 hydraulic properties of groundwater flow patterns under steady state flow. This

349 approach allows for a clearer understanding of the groundwater flow pattern response

350 to change in hydraulic properties (e.g., fault zones).

351 The model domain was divided into 39,056 unstructured grids, and the meshes were

352 required to be finer around the model boundaries and faults. Meshing quality was
353 examined to ensure that each fault zone contained multiple elements was fully
354 described in the model. Particle tracking was employed to investigate the differences in
355 groundwater flow paths between model scenarios. A total of 2,038 particles were set
356 up along the ground boundary, and their traces were recorded and exported.

357 4.3.2 Model results

358 Simulation results for the four scenarios are shown in Figure 4, where multiple types of
359 streamlines distributions are presented (only representative streamlines were showed
360 for distinguishability). Multiple types of streamlines (A, B, C, and D) are labelled to
361 illustrate the differences in groundwater flow patterns: A represents the streamlines
362 reaching deep positions; B represents the streamlines at the location of F11; C
363 represents the streamline at the location of F90; D represented the streamlines at the
364 location of F95.

365 While A streamlines are commonly observed in the *Homogeneous* scenario (Figure 4a),
366 they are absent in the layered scenarios. B streamlines in the *Layered: without faults*
367 scenario (Figure 4b) differ from those in the *Layered: low K fault* scenario (Figure 4c),
368 but they are similar to those in the *Layered: high K fault* scenario (Figure 4d), implying
369 impacts caused by the changes in permeability of the F11 fault core. In the *Layered:*

370 low K fault scenario, groundwater is hindered from flowing across the F11 fault zone
 371 but is driven along the damage zone. However, the B streamlines in *Layered: high K*
 372 *fault* indicate groundwater flowing across the F11 fault zone. The C and D streamlines
 373 in the *Layered: low K fault* and *Layered: high K fault* scenarios show the same
 374 distribution as F90 and F95 had identical permeabilities in these scenarios. In both
 375 scenarios, C and D streamlines suggest impeded groundwater flow compared with that
 376 in the *Layered: without faults* scenario.

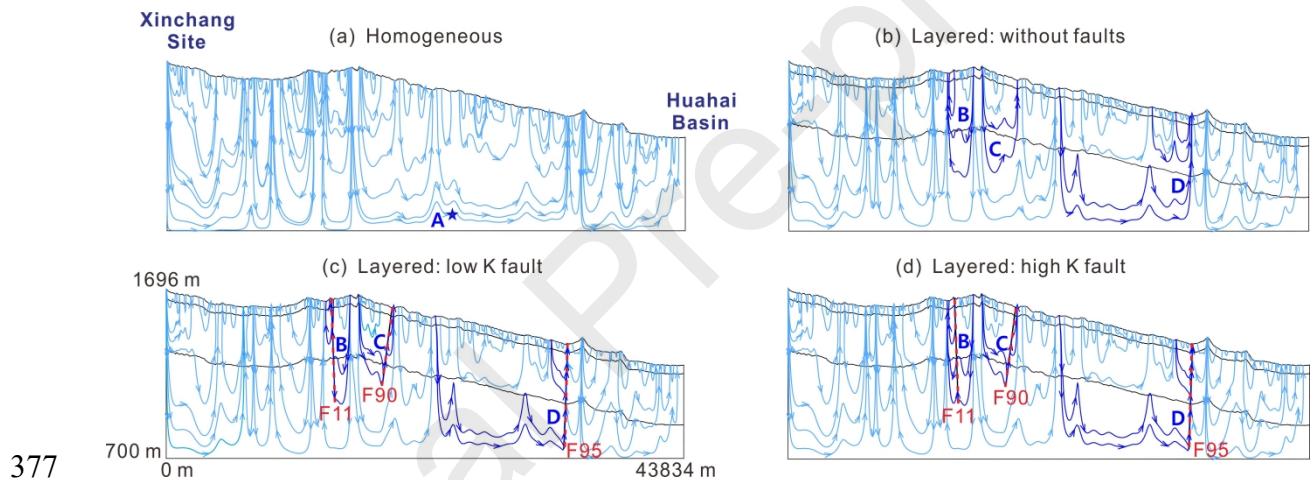


Figure 4. Streamline distributions of four model scenarios: A, B, and C represent observed streamlines to highlight the differences in groundwater flow patterns.

378 **5. Discussion**

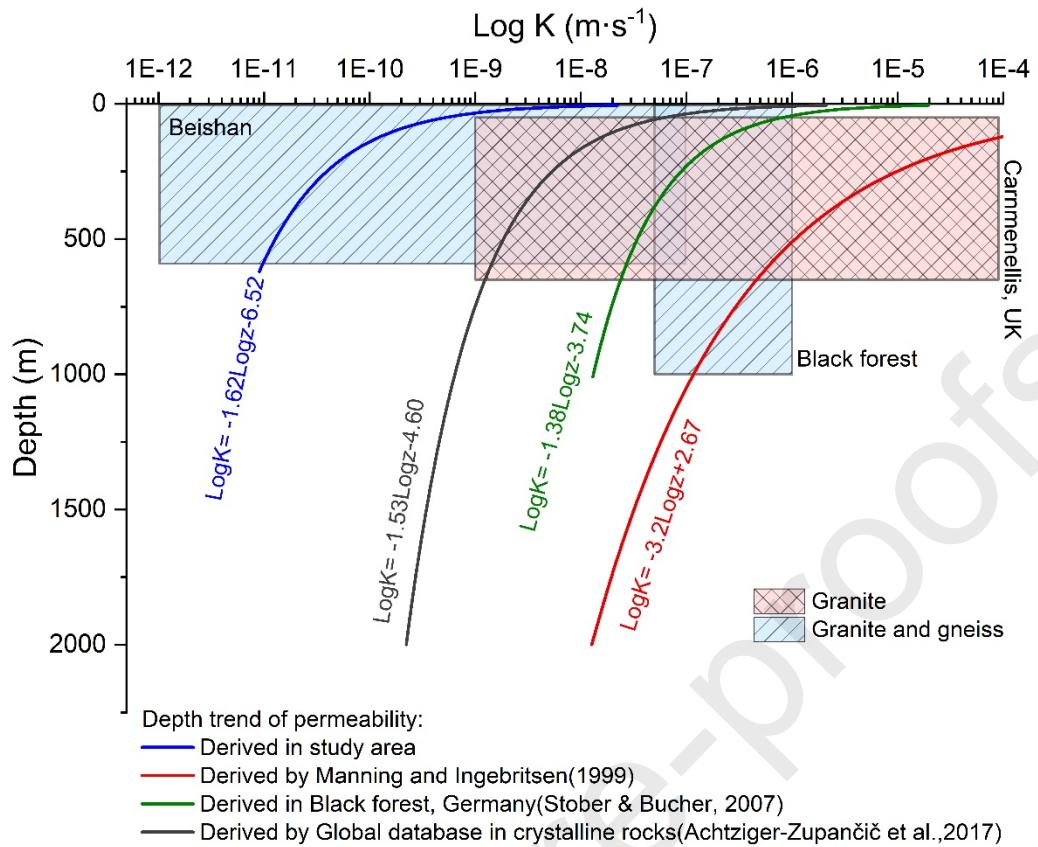
379 **5.1 Depth trend of Bedrock K in crystalline basement**

380 The crystalline basement, being mostly granite and gneiss, is generally low-

381 conductivity media where interconnected fracture porosity and permeability determine
382 groundwater flow behaviors (Rutqvist and Stephansson, 2003). The permeability of
383 crystalline rocks varies in space both horizontally and vertically due to fracture
384 interactions, and the vertical permeability is generally assumed to decrease with depth
385 (Achtziger-Zupančič et al., 2017; Brace, 1980; Manning and Ingebritsen, 1999;
386 Ranjram et al., 2015; Stober and Bucher, 2007). The decrease with depth was also
387 observed in the K obtained in crystalline bedrock composed of gneiss and granite within
388 600 mbgs in this study (Fig 2a). High hydraulic conductivity values were mostly
389 observed within depths of <100 m (especially within depths <50 m). The range between
390 the maximum and minimum K decreased with depth from approximately 9 orders of
391 magnitude (1E-14 to 1E -4 $\text{m}\cdot\text{s}^{-1}$) near the surface to approximately 4 orders of
392 magnitude in the deepest interval (1E-12 to 1E -8 $\text{m}\cdot\text{s}^{-1}$) As lithology may be of less
393 importance in crystalline rock permeability at near-surface depth (<1,000 m), the higher
394 and more scattered K values near the surface may indicate greater sensitivity to
395 weathering and tectonic setting alteration (Achtziger-Zupančič et al., 2017; Ranjram et
396 al., 2015).

397 A total of 91% of Bedrock K is distributed between $1.03 \text{ E-12 m}\cdot\text{s}^{-1} – 9.82 \text{ E-8 m}\cdot\text{s}^{-1}$,
398 which is generally less permeable than Carnmenellis Granite (Cornwall, UK) of similar
399 depth (Watkins, 2007). As shown in Figure 5, the K range in the study area is of smaller

400 values and larger variance than that in the Black Forest area of Germany, which has a
401 similar lithology of gneiss and granite (Stober and Bucher, 2007). The discrepancy is
402 also obvious in the logarithmic fits for the depth trend of permeability. The resulting
403 trend for Bedrock K in our study area yields a smaller slope and intercept than that
404 derived in the Black Forest area by Stober and Bucher (2007), as well as the depth trend
405 derived for a global database in crystalline rock by Achtziger- Zupančič et al. (2017).
406 The slope and intercept are also substantially significantly lower than the widely cited
407 curve derived by Manning and Ingebritsen (1999). This lack of agreement is expected
408 as these fits are derived to describe permeability at larger depths than those reported in
409 this study. Although Bedrock K in our study area verified the assumption of a decreased
410 trend with depth, the low predictive power ($R^2 = 0.19$) demonstrated the invalidity of a
411 consistent and generalizable equation capable of describing the K-z relationship in a
412 crystalline basement. Similar results were reported for the analysis of crystalline rock
413 datasets (Ranjram et al., 2015; Snowdon et al., 2021; Stober and Bucher, 2007).



414

Figure 5. Comparison of hydraulic conductivity (K) ranges and the depth trends in crystalline bedrock.

415 5.2 Permeability and flow behaviors in fault zones

416 The permeability and flow behaviors in three faults (F11, F90, and F95) in this
 417 mountain hydrogeological system are shown in Figures 3 and 4.

418 Fault zones created by brittle formation are composed of distinct components with
 419 different permeability: fault cores and damage zones (Bense et al., 2013; Caine et al.,
 420 1996; Rawling et al., 2001; Scibek, 2020). For a single fault, groundwater flows mainly

421 through connected open fractures in the damage zone; the proportion of damage zone
 422 thickness to total fault thickness (F_a) enables the description of fault architecture and
 423 flow behavior (Caine et al., 1996). With a F_a value close to 1 (0.98), the western part
 424 (B-B') of F95 is likely to be of the “distributed conduit” type. However, the same fault
 425 was identified to be a potential “barrier” according to the permeability ratio (Table 3)
 426 and simulated streamlines from 2D numerical modelling. This suggested the complex
 427 and combined role of F95 in this particular hydrogeological setting. With low
 428 conductivity for the general fault zone, the groundwater was hindered from flowing
 429 across the F95 towards the south in this two-dimensional model. Nevertheless, the
 430 existence of a relatively more permeable damage zone with higher conductivity (5.35
 431 $\text{E-7 m}\cdot\text{s}^{-1}$) in F95 suggests potential flow along the damage zone towards the southeast.

432 For F11, the discrepancy in fault core conductivity causes the spatial variability in
 433 permeability structures, and thus affects the flow behavior in numerical modelling.
 434 Groundwater flow was impeded from flowing across the F11 fault zone in the *Layered*:
 435 *Low K fault* scenario (corresponding to the measurements on the western part A-A'),
 436 acting as a barrier in MBR processes (Bresciani et al., 2018; Figueroa et al., 2021).
 437 However, the flow was allowed to pass the same fault zone in the *Layered: High K fault*
 438 scenario (corresponding to measurements on the western part B-B'), connecting
 439 groundwater from both sides of fault zone (Roques et al., 2014). Consequently, the F11

440 fault zone partially impedes groundwater flow from flowing south, likely acting as a
441 combined “conduit-barrier.” Similar flow behavior and discontinuity in permeability of
442 faults have been examined with numerical modelling (Mechal et al., 2016) and field
443 investigation (Caine et al., 2017). The large discontinuity of the fault in the eastern
444 Española Basin, Rio Grande rift, New Mexico, indicated that it was unlikely to
445 systematically impede groundwater flow (Caine et al., 2017).

446 According to simulated streamline C in Figure 4, F90 is likely a barrier for groundwater
447 flow in the study area. However, all three faults show only localized impact on
448 streamline distribution, indicating the limitation of faults’ effects on the
449 hydrogeological process for this particular mountain bedrock groundwater system.

450 *5.3 Possible MBR processes in the Beishan area*

451 The streamline distributions in Figure 4 indicates no groundwater flow directly from
452 the Xinchang Site to the Huahai Basin under the control of topography and generally
453 low hydraulic conductivity in the Beishan area. Streamline A observed in the
454 *Homogeneous* scenario was absent in all Layered scenarios, indicating the vertical
455 heterogeneity of K might hinder groundwater from developing deeper circulation and
456 therefore may prejudice diffuse MBR to the Hauhai Basin.

457 Although as an oblique-oriented fault, the F90 is likely to act as a hydraulic barrier to
30

458 diffuse MBR with available data. Groundwater flow towards the Huahai basin was
459 impeded from crossing the fault core zone of the obliquely oriented fault F95 in the 2D
460 section. However, the damage zone with relatively high conductivity and large
461 thickness may also function as a conduit driving groundwater flow within the connected
462 fractures, which is referred to as focused MBR. Consequently, the F95 is likely to act
463 as a combined “conduit-barrier”, impeding diffuse MBR while permitting focused
464 MBR.

465 The spatial variability in permeability results in the difference in the hydraulic role of
466 F11. As C streamlines shown in Fig 4, the F11 was unlikely to systematically and
467 significantly impede diffuse MBR by allowing groundwater flow across its core in
468 partial sections. Therefore, the F11 may also act as a combined “conduit-barrier” for
469 MBR in the study area.

470 Despite its spatial discontinuity and small thickness in the study area, the canyons of
471 alluvial sediment could present a potential flow path for focused MBR (Markovich et
472 al., 2019), especially within the mountain front area near the Huahai Basin. This process
473 corresponds to the groundwater recharge through focused infiltration contributed by
474 ephemeral streams, which is associated with rainy events or snowmelt (Taucare et al.,
475 2020) and is highly sensitive to local weather. Indeed, the absence of snow and rare
476 rainy events in the study area suppress focused MBR through canyons.

477 **6. Conclusion**

478 This study examines the potential flow paths of MBR processes, mainly focusing on
479 the vertical heterogeneity of K and the hydraulic role of fault zones in hydrogeological
480 settings. We also provide a series of hydraulic conductivity data obtained by in-situ
481 measurements from a crystalline mountain block system at various depths (0–592.34
482 m). We deciphered the flow paths originating from the Xinchang Site, Beishan area,
483 and feeding adjacent aquifers in the Huahai Basin using a permeability conceptual
484 model and numerical simulations of bedrock sections. These findings help to explain
485 the MBR processes critical in determining the safety of a future HLW disposal site. The
486 primary conclusions are as follows:

487

488 - Most Bedrock K (91%) is distributed between $1.03 \text{ E-12 m}\cdot\text{s}^{-1}$ – $9.82 \text{ E-8 m}\cdot\text{s}^{-1}$,
489 which is generally lower than that in other sites with similar depth or lithology
490 (Stober and Bucher, 2007; Watkins, 2007). Higher K values and larger variance
491 were observed at shallow depths (<100 m, and especially <50 m), supporting the
492 assumption that permeability is generally decreasing with depth. A logarithmic fit
493 to Bedrock K ($\text{Log } K = -1.62 \text{ Log } z(\text{m}) - 6.72$, $R^2 = 0.19$) shows a smaller slope and
494 intersect than those derived by Achtziger-Zupančič et al. (2017), Manning and

495 Ingebritsen (1999), and Stober and Bucher (2007). The discrepancy in data and
 496 trend line, as well as the low predictive power R^2 , suggesting the ineffectiveness of
 497 a consistent and generalizable relationship between hydraulic conductivity and
 498 depth in a crystalline basement.

499 - No direct groundwater flow from the Xinchang Site to the Huahai Basin was
 500 observed according to the simulated streamlines. The vertical heterogeneity of K
 501 distribution restrained groundwater from deeper circulation, and may suppress
 502 diffuse MBR in the study area.

503 - Spatial variability of measured K in fault cores of fault F11 induces discontinuity in
 504 permeability, and therefore the difference in hydraulic roles to MBR. F11 is
 505 approximately perpendicular to the MBR flow direction, whereas it might act as a
 506 combined “conduit-barrier” according to the distribution of simulated streamlines
 507 in study area (Figure 4).

508 - With low conductivity of general fault zones, obliquely oriented faults F90 and F95
 509 act as hydraulic barriers to diffuse MBR. However, the damage zone of relatively
 510 high conductivity could function as a conduit driving groundwater flow within
 511 connected fractures, promoting focused MBR of study area.

512 In summary, based on in-situ K data ($n = 555$), this study suggests the possible flow
 513 paths of MBR in a crystalline mountain block system, providing insights into the

514 characteristics of K in mountain bedrock. The study also provides insights into the
515 localized effects and spatially variable roles of fault zones in hydrogeological processes
516 within this particular hydrogeological configuration in Beishan, China. In addition, the
517 hydraulic conductivity data presented here can provide information on the subsurface
518 properties of mountain block systems in crystalline areas, and further facilitate the
519 characterization and quantification of mountain block recharge.

520 **CRediT authorship contribution statement**

521 **Yunmei Fu:** Conceptualization, Investigation, Methodology, Software, Formal
522 analysis, Visualization, Writing - original draft. **Yanhui Dong:** Funding acquisition,
523 Methodology, Project administration, Supervision, Writing - review and editing.
524 **Liheng Wang:** Investigation, Writing - review and editing. **Olivier Bour:** Visualization,
525 Writing - review and editing. **Maria V. Klepikova:** Visualization, Writing - review and
526 editing. **Zihua Zong:** Resources, Investigation. **Zhifang Xu:** Supervision, Writing -
527 review and editing. **Zichao Zhou:** Resources, Investigation.

528 **Declaration of Interest**

529 The authors declare that they have no known competing financial interests or personal
530 relationships that could have appeared to influence the work reported in this paper.

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738 **Abstract**

739 The process wherein groundwater flowing from mountain bedrock into lowland and
 740 adjacent alluvial aquifers, known as mountain-block recharge (MBR), is found across
 741 various climatic and geological settings. An understanding of the potential groundwater
 742 flow paths in mountain block systems is necessary for comprehending MBR spatial
 743 distribution. However, poorly characterized mountain block hydraulic properties, and
 744 especially a lack of direct measurements of hydraulic conductivity (K) at depths >200
 745 m, limit the characterization and quantifications of the MBR processes. In this study,
 746 we analyze hydraulic data set, namely 555 in-situ K measurements at various depths
 747 from two borehole sections extending from mountain block to mountain front in a
 748 potential disposal site for high-level radioactive waste. The K dataset was categorized
 749 into two groups: one for bedrock and another for fault zones, which was further
 750 classified into fault core K , damage zone K , and general fault zone K . Using a
 751 permeability conceptual model and multiple scenarios numerical modelling, this study
 752 examined the potential flow paths of MBR processes, mainly focusing on the
 753 characteristics of K in bedrocks and the hydraulic role of fault zones in mountain block

systems. The distribution of Bedrock K supports the assumption of decreased trend with depth. A logarithmic fit through Bedrock K and depth pairs resulted in $\text{Log}(K) = -1.62 * \text{Log}(z) - 6.52$, with low predictive power. This study illustrated the localized effects and spatially variable roles of fault zones in MBR within this particular hydrogeological configuration in Beishan, China. Our results provide insights into the MBR process in crystalline mountain block systems. Additionally, the hydraulic conductivity presented here provides data on the subsurface properties of mountain block systems in a crystalline area, and further facilitates the characterization and quantification of mountain-block recharge.

763 **Keywords:** mountain block recharge, mountain hydrogeology, fractured aquifer

764

765 **Declaration of interests**

766

767 The authors declare that they have no known competing financial interests or personal
768 relationships that could have appeared to influence the work reported in this paper.

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770 The authors declare the following financial interests/personal relationships which may be
771 considered as potential competing interests:
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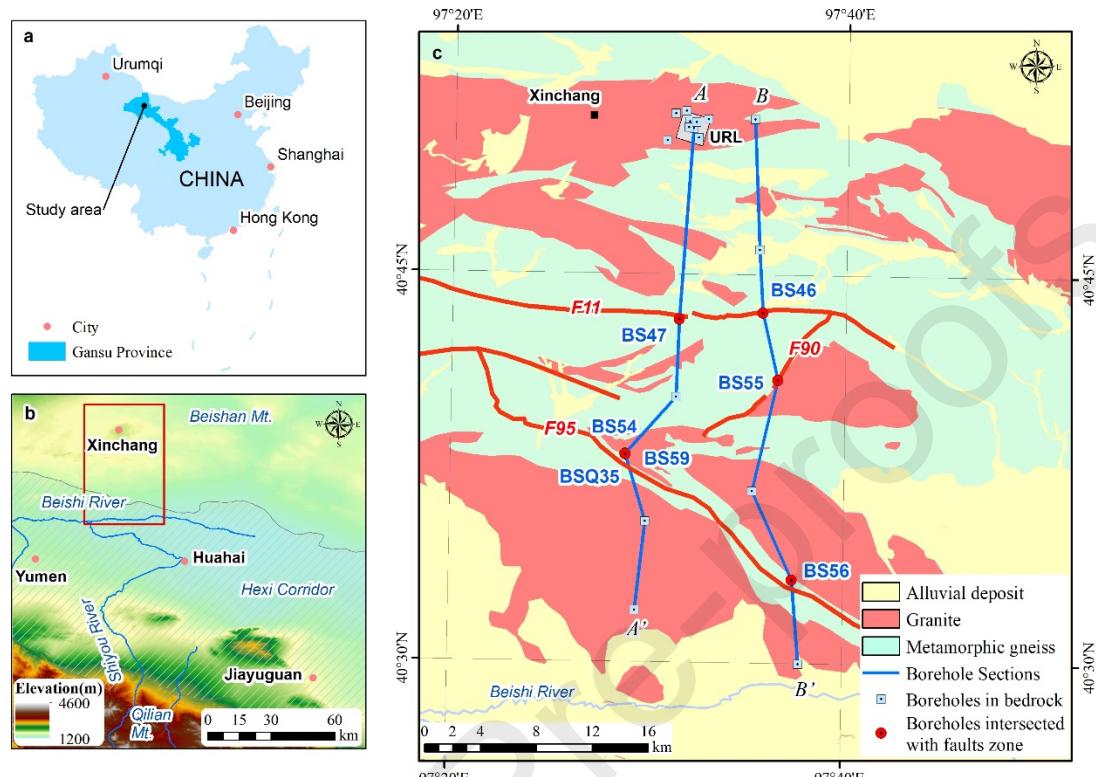
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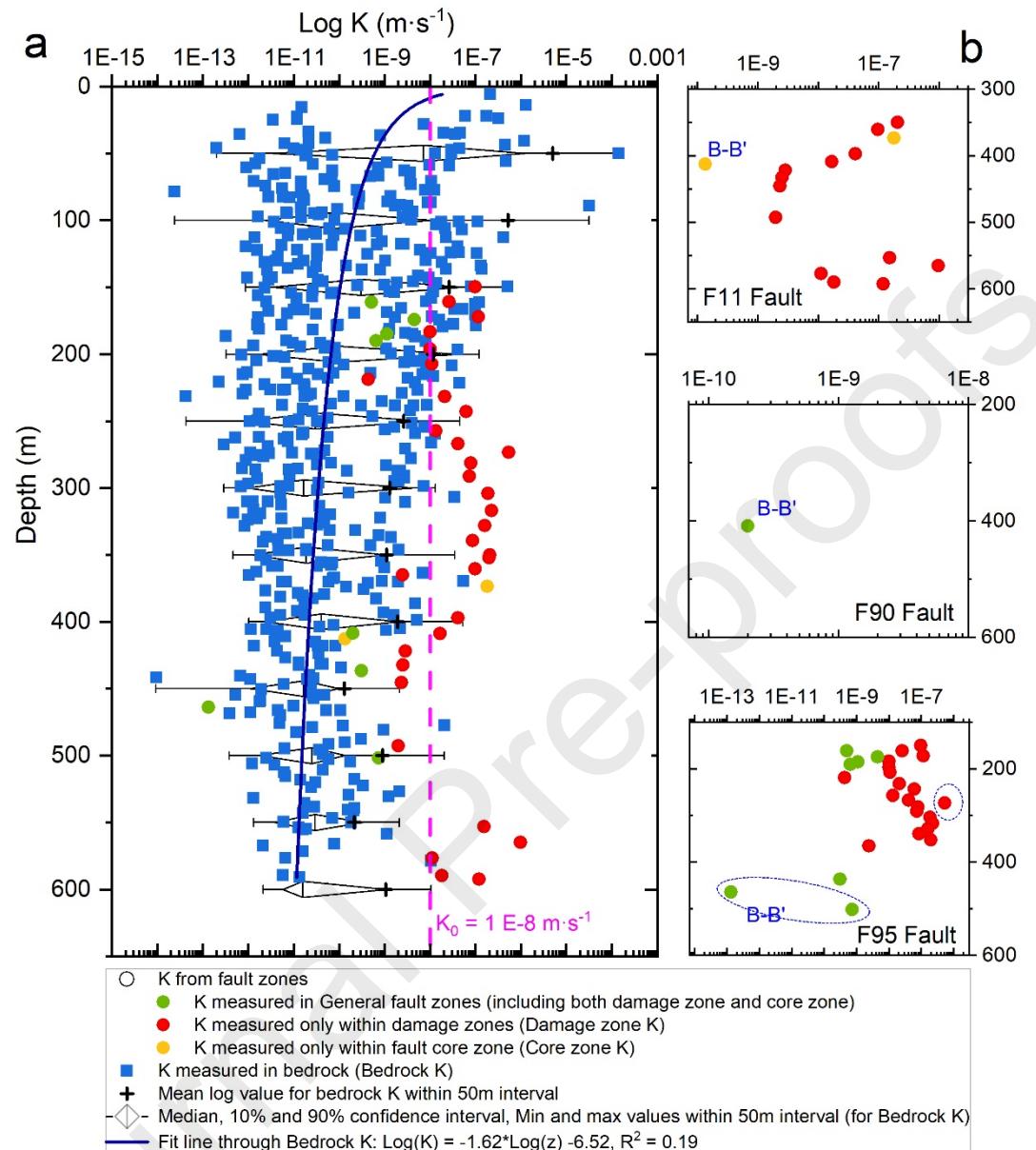
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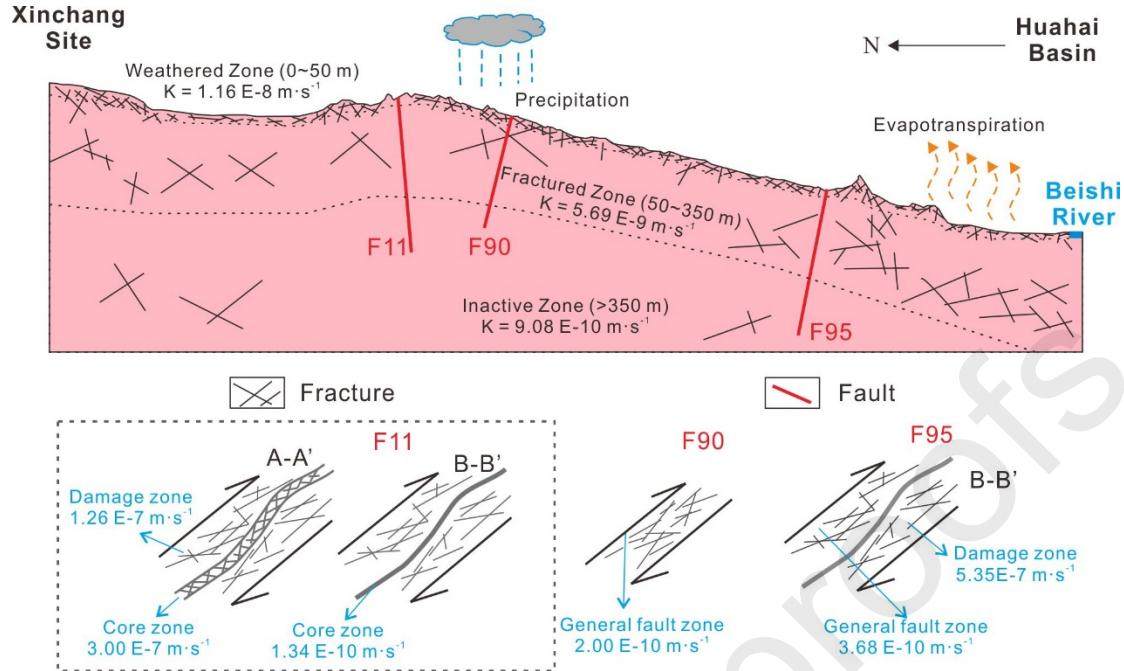


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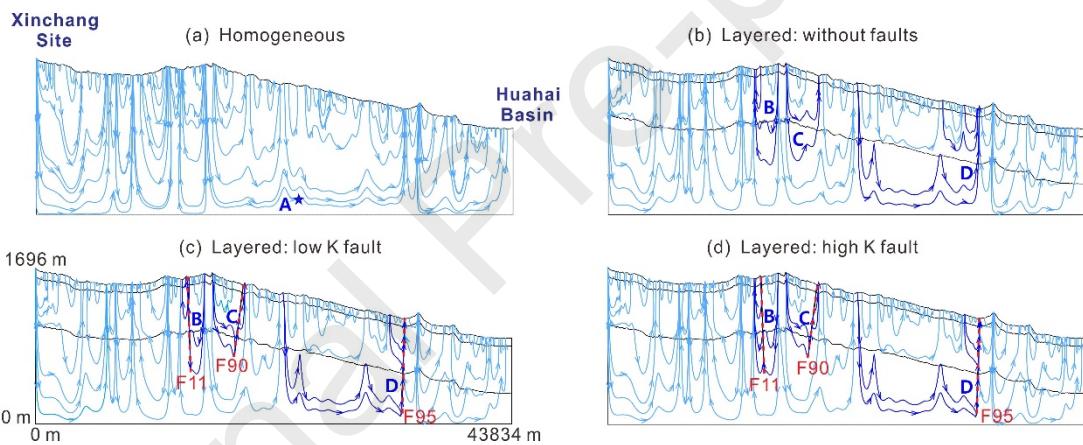


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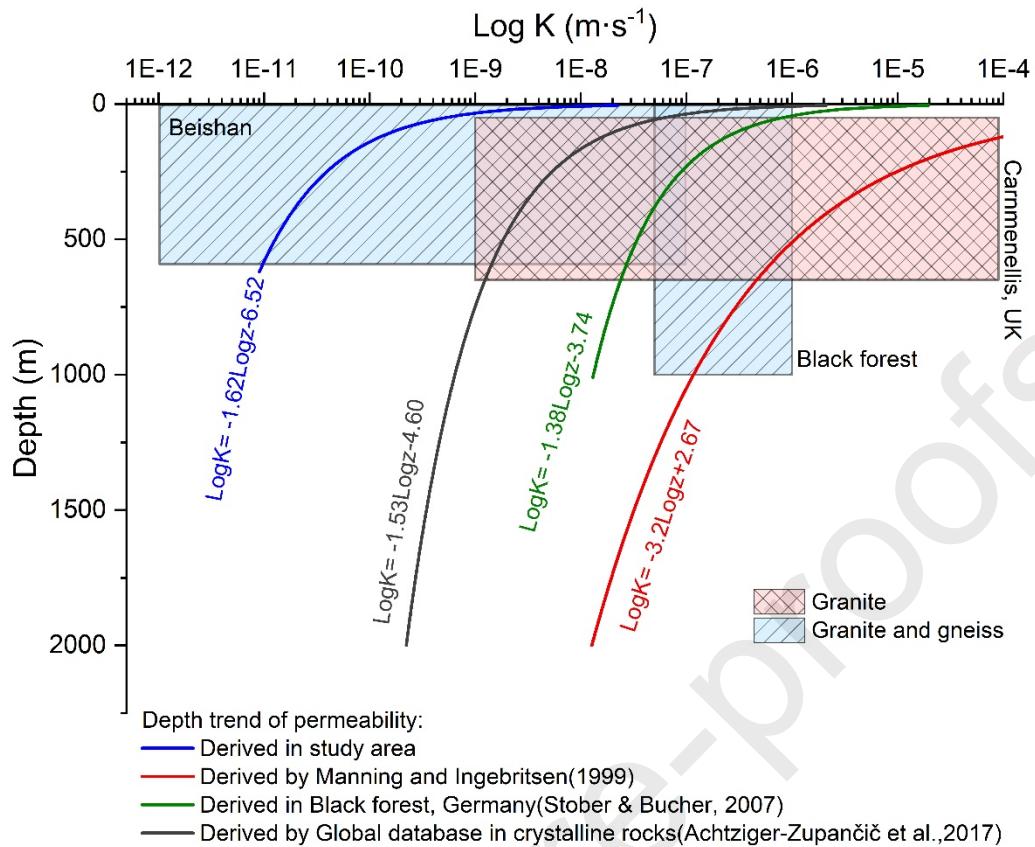
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784 **Highlights**

- Potential flow paths of MBR process in crystalline mountain block systems were explored based on hydraulic conductivity data up to ~592.34 m depth.
- Characteristics of hydraulic conductivity for bedrock and fault zones including core zones and damage zones were reported.
- Spatial discontinuities in the permeability may exist for the same fault, which lead to its role can be either a conduit or a barrier in the MBR process.

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