

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

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## Research papers

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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
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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

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## 23 Abstract

The process wherein groundwater flowing from mountain bedrock into lowland and adjacent alluvial aquifers, known as mountain-block recharge (MBR), is found across various climatic and geological settings. An understanding of the potential groundwater flow paths in mountain block systems is necessary for comprehending MBR spatial distribution. However, poorly characterized mountain block hydraulic properties, and 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 $Log(K) = -$
41	1.62*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.

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

# **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; Viviroli 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 4

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)distribution within mountain bedrock and the role that fault zones play being two vital 72 factors (Gleeson and Manning, 2008; Markovich et al., 2019; Welch et al., 2012; 73 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, 2008; Haitjema and Mitchell-Bruker, 2005; Markovich et al., 2019; Welch et al., 2012; 76 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., 2019; Welch et al., 2012). The existence of an "active" zone with  $K > 10^{-8}$  m<sup>-1</sup> where 80 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 fault zone to enter the adjacent aquifers (Chowdhury et al., 2008; Delinom, 2009; 86

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

100 mountain front (Markovich et al., 2019; Yao et al., 2017).

99

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

zones and data limitation, particularly of subsurface data from the mountain block and

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 CO <sub>2</sub> geological
113	storage target depths are $\geq 800$ 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.

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

disposal. Based on a permeability conceptual model and numerical modelling built onin-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.

130

## 129 2 Study area



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.

This study was conducted in the Beishan area situated in the Gansu Province of
 8

132	northwestern China (Fig 1a). The study area is an inland mountain range covering an
133	area of approximately 3,973.9 km <sup>2</sup> 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 $>100 \text{ km}^2$ 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

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

148 ]	Гhe	Beishan	area	is	characterized	by	an	arid	climate	with	an	annual	average
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- 149 precipitation of 73.1 mm $\cdot$ yr<sup>-1</sup> 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

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

155

Several faults have been identified in the study area, including two major faults (F11 156 157 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 the secondary faults of F11 and is located in granite and metamorphic gneiss (Gansu 162 163 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 Huahai Basin (Gansu Geology Survey, 1978; Guo et al., 2003; Guo et al., 2014; Wang et al., 2018b). 166

Table 1. Fault kinematics and architectures.

Section Fault Strike Dip Geology

Thickness

			JC	buillai Fie-piooi	.5		
					Total zone (m)	Fault core (m)	Damage zone (m)
	F11	W-SW	70	Metamorphic gneiss	-	10.6	-
A-A	F95	NW-SE	78	Metamorphic gneiss	64.4	30.2	34.2
	F11	W-SW	60	Metamorphic gneiss	-	1.4	
	500		(0)	Granite &			
R-R	F90	NE-SW	60	gneiss	52.4	-	-
	F95	NW-SE	75	Metamorphic gneiss	67.0	1.6	65.4

Hydrogeochemical characteristics reveal the evolution processes of groundwater by
recording the interaction between groundwater and the aquifer medium. Accordingly,
the hydrogeochemical data of groundwater in the Beishan area were comprehensively
collected from published literature, revealing a range of pH values from 7.39 to 10.14,
groundwater temperature between 8 and 17 °C, and a total dissolved solid (TDS)
content of 0.7–19.0 g·L<sup>-1</sup> (Guo et al., 2014; Li, 2020; Wang et al., 2018b; Wang, 2015).
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 (Table 1). Boreholes were drilled through the surface weathering rock and into the 182 183 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, 2020; Scibek et al., 2016). The measuring intervals of in-situ tests differ from 12 to 50 187 188 m along the boreholes, and were also extended to 202 m to investigate the fault zones intersected by the boreholes. 189

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.

The Bedrock *K* data (n = 512, shown as blue squares in Figure 2a) was divided into measurement depth intervals of 50 m, and the arithmetic mean, median, 10% and 90% confidence distribution of each interval were calculated. A linear regression of log hydraulic conductivity (log *K*) over log depth (log *z*) was performed on the Bedrock *K* 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

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

216 From a hydrogeological perspective, a domain can be viewed as a pervious formation with  $K \ge 1.00 \text{ E-8 m} \cdot \text{s}^{-1}$ , where active groundwater flow may be produced (Katsura et 217 al., 2009; Markovich et al., 2019; Welch and Allen, 2014). Therefore, a threshold value 218 of  $K_0 = 1.00$  E-8 m·s<sup>-1</sup> was adapted to indicating K's relative difference by depth in 219 bedrock. The probability  $K > K_0$  (P) and the arithmetic mean K value of every 50 m 220 221 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 vertical permeability structure of the mountain block in the study area was then divided 223 224 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 of  $K < K_0$ , where active groundwater may not be produced). 226

The permeability ratios (Scibek, 2020) can be used to quantify the "conduit" or "barrier"
 14

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

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

234 *3.2 Groundwater flow analysis– numerical modelling* 

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

## **4. Results**

*4.1 Characteristics of hydraulic conductivity* 

243 4.1.1 Hydraulic conductivity of bedrock



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.

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

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

256 4.1.2 Fault zone hydraulic conductivity

Figure 2b shows 43 *K* measured in fault zones (2 Core zone *K*, 33 Damage zone *K*, and
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 E-7 m $\cdot$ s <sup>-1</sup> in the western part (A-A'), and 1.34 E-10 m $\cdot$ s <sup>-1</sup> 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	$(1.97 \text{ E-9 m} \cdot \text{s}^{-1} - 9.71 \text{ E-7 m} \cdot \text{s}^{-1}).$
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 E-10 m·s <sup>-1</sup> . For F95, General fault
266	zone K obtained from the western part (B-B') ranged from 1.33 E-13 m·s <sup>-1</sup> to 7.31 E-
267	10 m $\cdot$ s <sup>-1</sup> , with the ones from the western part (A-A') showing a larger variance. Damage
268	zone <i>K</i> were all centralized between 4.31 E-10 m·s <sup>-1</sup> and 5.35 E-7 m·s <sup>-1</sup> .

269 4.2 Mountain-basin conceptual model

270 4.2.1 Bedrock permeability structure

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

277	The arithmetic mean value of <i>K</i> was 4.80 E-6 m·s <sup>-1</sup> , 1.01 E-7 m·s <sup>-1</sup> , and 9.08 E-10 m·s <sup>-1</sup>
278	for the Weathered Zone, Fractured Zone, and Inactive Zone respectively. The
279	proportion of $K \ge K_0$ 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 E-8 m·s <sup>-1</sup> for the Weathered Zone, 5.69 E-9 m·s <sup>-1</sup> for the Fractured Zone, and 9.08
285	E-10 $m \cdot s^{-1}$ for the Inactive Zone.

286 4.2.2 Permeability structure of faults

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

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 19

295	groundwater	flow	and	acts	as	a	"barrier".	K	ratio	of	-0.96	for	F90	also	suggests	а
296	potential "ba	rrier"	for g	groun	dw	ate	er 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
	F11	-	3.00E-7	4.15E-10*	2.86
A-A'	F95	1.41E-9*	-	7.89E-9*	-0.75
	F11	-	1.34E-10	8.74E-9*	-1.81
B-B'	F90	2.00E-10	-	1.84E-9*	-0.96
	F95	3.68E-10*	0	1.25E-9*	-0.53

## 297 4.2.3 Conceptual model

A conceptual hydrogeological model of the study area is shown in Figure 3. Based on 298 299 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 hydraulic conductivity of F95 and F90 were labelled according to the information 303 304 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 flow patterns in the study area. 306 20



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
  - 21

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 E-8 $m \cdot s^{-1}$ ) 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 E-10 m·s <sup>-1</sup> ) 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 E-7 m·s <sup>-1</sup> ) was used for damage zone.
334	For F11, the lower measured value of 1.34 E-10 m $\cdot$ s <sup>-1</sup> was selected to represent the
335	permeability of F11 fault core (Figure 3), and the damage zone hydraulic
336	conductivity was 1.26 E-7 m $\cdot$ s <sup>-1</sup> .
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 $3.00 \text{ E-7 m} \cdot \text{s}^{-1}$ .
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 23

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.

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

24

*low K fault* scenario, groundwater is hindered from flowing across the F11 fault zone but is driven along the damage zone. However, the B streamlines in *Layered: high K fault* indicate groundwater flowing across the F11 fault zone. The C and D streamlines in the *Layered: low K fault* and *Layered: high K fault* scenarios show the same distribution as F90 and F95 had identical permeabilities in these scenarios. In both scenarios, C and D streamlines suggest impeded groundwater flow compared with that 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-25

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 m·s-1) near the surface to approximately 4 orders of
392	magnitude in the deepest interval (1E-12 to 1E -8 m·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).

A total of 91% of Bedrock *K* is distributed between 1.03 E-12 m·s<sup>-1</sup> – 9.82 E-8 m·s<sup>-1</sup>, which is generally less permeable than Carnmenellis Granite (Cornwall, UK) of similar 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).



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
   28

421	through connected open fractures in the damage zone; the proportion of damage zone
422	thickness to total fault thickness (F <sub>a</sub> ) 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	E-7 m $\cdot$ s <sup>-1</sup> ) 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).

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

#### 5.3 Possible MBR processes in the Beishan area 450

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

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.

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

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

## 477 **6.** Conclusion

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

487

488 -	Most Bedrock K (91%) is distributed between 1.03 E-12 m·s <sup>-1</sup> –9.82 E-8 m·s <sup>-1</sup> ,
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 (Log K = -1.62 Log z(m) - 6.72, R2 = 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 <sup>2</sup> , 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 rescible flow
312	m	summary, based on m-situ $\kappa$ data (n – 355), this study suggests the possible flow

513 paths of MBR in a crystalline mountain block system, providing insights into the 33

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.

#### **Declaration of Interest** 528

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 flow paths in mountain block systems is necessary for comprehending MBR spatial 742 distribution. However, poorly characterized mountain block hydraulic properties, and 743 744 especially a lack of direct measurements of hydraulic conductivity (K) at depths >200m, limit the characterization and quantifications of the MBR processes. In this study, 745 we analyze hydraulic data set, namely 555 in-situ K measurements at various depths 746 747 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 classified into fault core K, damage zone K, and general fault zone K. Using a 750 751 permeability conceptual model and multiple scenarios numerical modelling, this study examined the potential flow paths of MBR processes, mainly focusing on the 752 753 characteristics of *K* in bedrocks and the hydraulic role of fault zones in mountain block 47

754	systems. The distribution of Bedrock $K$ supports the assumption of decreased trend with
755	depth. A logarithmic fit through Bedrock K and depth pairs resulted in $Log(K) = -$
756	1.62*Log(z) - 6.52, with low predictive power. This study illustrated the localized
757	effects and spatially variable roles of fault zones in MBR within this particular
758	hydrogeological configuration in Beishan, China. Our results provide insights into the
759	MBR process in crystalline mountain block systems. Additionally, the hydraulic
760	conductivity presented here provides data on the subsurface properties of mountain
761	block systems in a crystalline area, and further facilitates the characterization and
762	quantification of mountain-block recharge.

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

# 764

765	Declaration of interests
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767	It is 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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