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Assessment of rock glaciers, water storage, and permafrost distribution in Guokalariju, Tibetan Plateau

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Abstract. Rock glaciers are important hydrological reserves in arid and semi-arid regions, and their activity status can indicate the existence of permafrost. In order to explore the development mechanism of rock glaciers in the semi-arid and humid transition region, this paper provides a more detailed rock glaciers inventory of Guokalariju (GKLRJ) in the Tibetan Plateau. In addition, the water volume equivalent (WVEQ) and permafrost distribution probability of GKLRJ were estimated for the first time. About 5053 rock glaciers were identified, covering a total area of about 428.71 km^2 at 4600-5300 m a.s.l. Most of the rock glaciers are considered talus-derived and distributed in the semi-arid region. Their development strongly depends on precipitation and topography, which are more located in the climate transition zone and dominated by the west-facing slope. A huge potential hydrological significance of those rock glaciers was found in our research, and the ratio of WVEQ in the intact rock glaciers to glaciers is about 1:1.63. Permafrost probably exists above the 4476 m a.s.l, which has shown an apparent degradation trend in the central and western regions. These findings will provide an important reference for global rock glacier assessment and local water resources management.

1 Introduction

Rock glaciers are periglacial landforms distributed above the timberline in the alpine mountains and formed by rocks and ice that move down the slope driven by gravity (French 2007; RGIK, 2021). They are often considered to be a sign of permafrost presence in mountainous areas and represent a unique result of the stable transport of ice and debris (Barsch, 1992, 1996; Kääb *et al.*, 1997; Schmid *et al.*, 2015). Their lowest elevations are often considered the lower limit of discontinuous permafrost (Giardino and Vitek, 1988; Barsch, 1996; Selley *et al.*, 2018; Baral *et al.*,2019; Hassan *et al.*,2021), and their activity state (intact or relict) can be used in the Permafrost Zonation Index (PZI) models to predict the likelihood of permafrost occurrence where field observation data are scarce (Cao *et al.*, 2021; Boeckli *et*

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al., 2012a). The large-scale distribution of active rock glaciers is influenced by the complex interaction of climate and topographic factors, but is insensitive to the interannual and seasonal fluctuations of temperature and precipitation (Schrott, 1996; Millar and Westfall, 2008; Pandey, 2019). In the context of global climate change, the stability of rock glaciers and permafrost may also be affected, thus affecting slope stability, vegetation coverage, runoff patterns, and water quality, then causing periodic landslides, debris flows, floods, and other geological disasters (Barsch, 1996; Schoeneich *et al.*, 2015; Blöthe *et al.*,2019; Hassan *et al.*, 2021). Therefore, exploring their spatial distribution and evolution is significant for paleoclimate modelling, disaster risk assessment, and infrastructure maintenance (Arenson and Jakob, 2010; Colucci *et al.*, 2016; Selley *et al.*, 2018; Alcalá-Reygosa, 2019). Furthermore, the insulating effect of the active layer of rock glaciers enables it to act as an essential hydrological reserve in arid and semi-arid mountainous areas prolonging long-term water storage in high mountain systems (Bolch and Marchenko, 2009; Berthling, 2011; Bonnaventure and Lamoureux, 2013; Millar and Westfall, 2013), their presence and abundance can affect the amount and properties of runoff from high mountain watersheds (Bosson and Lambiel, 2016; Jones *et al.*, 2019b).

Tibetan Plateau (TP) is the leading distribution area of periglacial landform worldwide and a sensitive area for climate change (Cui *et al.*, 2019; Yao *et al.*, 2019). Detailed inventories of rock glaciers have been previously mapped in the regions of the Gangdise Mountains (Zhang *et al.*, 2022), Daxue Shan (Ran and Liu, 2018), Nyainqêntanglha Range (Reinosch *et al.*, 2021), and Nepalese Himalaya (Jones *et al.*, 2018b). The Yarlung Zangbo River basin is one of the regions with the most concentration of modern glaciers on the TP and the fastest rapid geomorphic evolution on the earth today (Ji *et al.*, 1999; Korup and Montgomery, 2008; Yu *et al.*, 2011; Long *et al.*, 2022). Guokalariju (GKLRJ) is a typical region for the study of rock glaciers of TP. Located between Yarlung Zangbo River - Lhasa River - Niyang River, GKLRJ is an important window to study the periglacial geomorphology of the transition belt between the plateau semi-arid and humid region. The previous study has mapped and characterized the spatial distribution of rock glaciers in the Yarlung Zangbo River watershed (Guo, 2019). However, there is still a lack of a systematic and detailed rock glaciers inventory, and the development mechanism and indicative environmental significance of rock glaciers are still unclear. Thus, this study aims to (i) map rock glaciers in GLKRJ more comprehensively and systematically, (ii) explore the development mechanism of rock glaciers in the transitional belt dominated by the Indian summer monsoon (ISM), (iii) assess the hydrological significance of rock glaciers compared to glaciers, and (iv) predict the occurrence

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probability of the permafrost.

2 Study area

GKLRJ is located between 92.916°N-93.276°N and 29.287°E-29.438°E in the southeast TP, adjacent to the Himalayas in the south and Nyainqêntanglha Range in the north. It is the eastern extension of the Gangdise Mountains as well as the watershed of the Yarlung Zangbo River and its tributary Niyang-Lhasa River, belongs to the high mountain plateau-lake basin-wide valley area in the middle and upper reaches of the Yarlung Zangbo River and Nujiang River (Xiang *et al.*, 2013). In the subdivision of the tectonic unit, GKLRJ is located in the eastern part of the Ladakh- Kailas-Xiachayu magmatic arc belt (Ⅶ1-6) of the Gangdise-Himalayan collisional orogen, and has undergone the tectonic evolution process of the development of the Gangdise-Himalayan archipelagic arc-basin systems, back-arc spreading, arc-arc collision and arc-continental collision from the Late Paleozoic to the Mesozoic (Pan *et al.*, 2013). The main rock types include Late Cretaceous quartz monzonite, Eocene monzonite, and Eocene biotite granite. Mainly dominated by the ISM, the middle and west parts of GKLRJ belong to the temperate semi-arid region of the plateau, while the eastern part belongs to the temperate humid region (Zheng *et al.*, 2010). The mean annual temperature (MAAT) is 6-10℃, and the annual mean minimum temperature is -2℃~5℃. The mean annual precipitation is about 400 mm, with a decreasing trend from east to west.

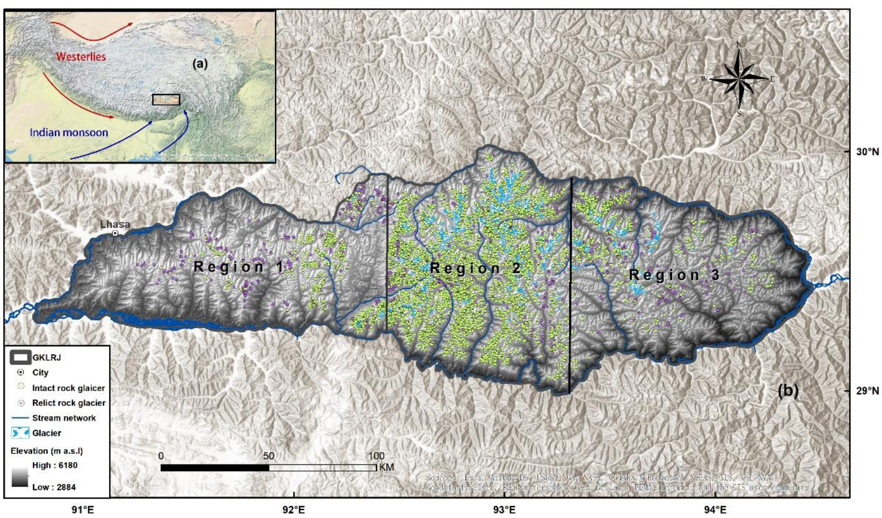

Figure 1: (a) The location of GKLRJ in the TP. (b) The three sub-regions and the spatial distributions of streams. Rock glaciers are categorised to green (intact rock glaciers), purple (relict rock glaciers), glaciers are shown in bule and white. Maps were created using ArcGIS® software by Esri.

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As shown in Figure 1(b), GKLRJ can be further divided into R1, R2, and R3 based on the geographical spatial pattern, where R1 and R2 are bounded by the eastern margin rift of the Oiga basin, R2 and R3 are bounded by Niang River, a tributary of the Niyang River. In R1, the mean altitude of is about 4580 m a.s.l., the mean annual precipitation is approximately 284 mm, and the mean annual ground temperature (MAGT) is about 1.6℃. The magnitude of mountain uplift caused by rifting activities and the down-cutting intensity of the Yarlung Zangbo River in R2 are all significantly greater than that in R1. Most of the mountains in the region are taller than 5500 m a.s.l. and are accompanied by modern glacier development. The mean altitude of R2 is about 4893 m a.s.l., the mean annual precipitation is about 386 mm, and the MAGT is about -0.07℃. Compared with the others, R3 has a lower altitude and abundant precipitation, with a mean altitude of about 4398 m a.s.l., mean annual precipitation of about 534 mm, and the MAGT is about 0℃.

3 Material and methods

3.1 Rock glaciers inventory, classification, and database

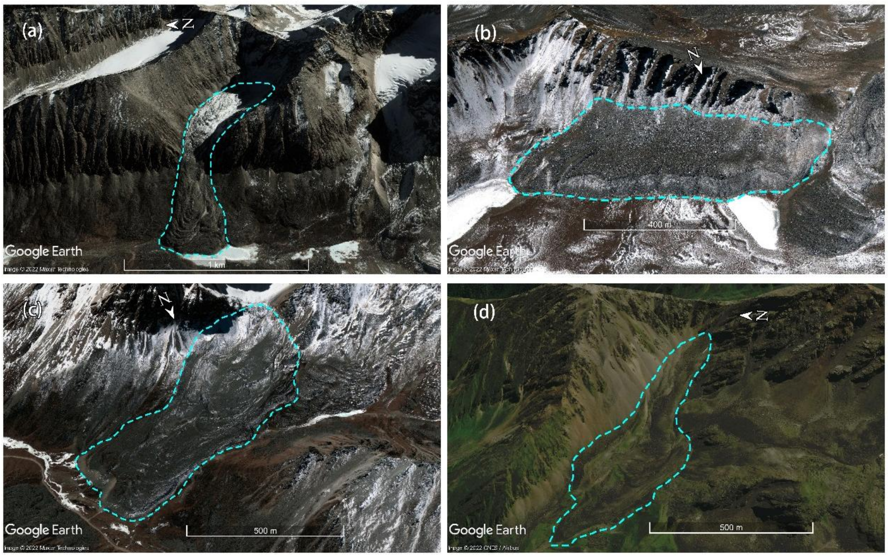

Figure 2: Example images of different types of rock glaciers in GKLRJ. (a)Intact debris-derived rock glacier, (b) Intact talus-derived rock glacier, (c) Relict debris-derived rock glacier, (d)Relict talus-derived rock glacier. Image ©Google Earth.

Firstly, we used high-resolution ©Google Earth remote sensing images (February 2009 to December 2020) to compile the list of rock glaciers in GKLRJ due to the lack of accurate field observation and related data on rock glaciers dynamics (Selley *et al.*, 2018; Magori *et al.,* 2020; Hassan *et al.,* 2021). The identified rock glaciers were digitized from the front toe up to the lower end of the rooting zone in Google Earth, and their activity statuses were determined according to the front slope, vegetation coverage, surface flow structures, rock glacier body, and other geomorphic indicators. Secondly, we divided rock glaciers into two types (intact/relict) according to the method of Scotti *et al.* (2013). The active and inactive types are designated together as 'intact rock glaciers' in this study (Haeberli, 1985; Pandey, 2019). The intact rock glaciers usually have steep front slopes and lateral edges, an absence of vegetation cover, and apparent flow structures such as ridges and furrows. The relict rock glaciers relatively have gentle slopes, poorly defined lateral margins, subdued topography, and less prominent flow structures (Scotti *et al.*, 2013; Baral *et al.*, 2019). Based on the source of the sedimentary material, we divided rock glaciers into four types: (A) intact debris-derived rock glacier (hereafter 'ID'), (B) intact talus-derived rock glacier (hereafter 'IT'), (C) relict debris-derived rock glacier (hereafter 'RD'), (D) relict talus-derived rock glacier (hereafter 'RT'). Thirdly, we loaded them to ArcGIS 10.7 and calculated their parameters (i.e., area, length, width) in Excel to further divide the geometry types according to the length-width ratios. Rock glaciers with length/width <1 are classified as lobate-shaped rock glaciers (hereafter 'L'), while those with length/width >1 are classified as tongue-shaped rock glaciers (hereafter 'T') (Baroni *et al.*, 2004; Nyenhuis *et al.*, 2005; Scotti *et al.,* 2013). To further reduce the subjectivity associated with the identification, digitization, and classification of landforms introduced by factors such as cloud cover, snowfall coverage, and image quality in the inventory (Schmid et al., 2015; Jones *et al.*, 2018b; Brardinoni *et al.*, 2019), we assessed the uncertainty for each rock glacier and recorded the Certainty Index (table.1) in the attribute table. And each rock glacier categorised as "virtual certainty" has been rechecked in Mapcarta. In addition, we used the 1984 UTM Zone 46N projection system in ArcGIS 10.7 to extract the topographic attributes. The attributes such as latitude, longitude, altitude, area, slope, and aspect were calculated based on the ASTGTM2 DEM data, and the aspects were recoded into eight categories (N, NE, E, SE, S, SW, W, NW). Finally, statistical analysis of the above attribute information was conducted by SPSS 27.0 software, and the Pearson correlation coefficient was used to evaluate the correlation between topographic attributes.

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Table.1 Certainty Index applied to each rock glaciers (Jones et al., 2018b)

Parameter	Parameter options (index code)		
	1 point	2 points	3 points
External boundary	None (ON)	Vague (OV)	Clear (OC)
Snow coverage	Snow (SS)	Partial (SP)	None (SN)
Longitudinal flow structure	None (LN)	Vague (LV)	Clear (LC)
Transverse flow structure	None (TN)	Vague (TV)	Clear (TC)
Front slope	Unclear (FU)	Gentle (FG)	Steep (FS)
Certainty Index score	Medium certainty (MC)	High certainty (HC)	Virtual certainty (VC)
	⩽5	6 to 10	⩾11

3.2 Estimating hydrological stores

We calculated the water content (water volume equivalent, WVEQ [km^3]) of the intact rock glaciers to estimate their hydrologic significance in GKLRJ (Jones *et al.*, 2018b). Ground-penetrating radar (GPR), seismic refraction tomography (SRT), electrical resistivity tomography (ERT) and other geophysical techniques are widely used today and provide new insights into understanding the ice volume content of rock glaciers (Janke *et al.*, 2015; Emmert and Kneisel, 2017; Bolch *et al.*, 2019; Buckel *et al.*, 2021; Halla *et al.*, 2021; Mathys *et al.*, 2022). However, it is still difficult to apply such methods to large-scale field-based research in TP. Therefore, we chose the empirical rule that has been widely used worldwide to estimate the ice volume of active rock glaciers in GKLRJ (Brenning, 2005a, 2005b; Azócar and Brenning, 2010; Rangecroft et al., 2015). This method first requires a calculation by multiplying the estimated thickness, surface area, and estimated ice content of rock glaciers. Since the thickness of each rock glacier was unknown, we estimated it by applying the empirical rule established by Brenning (2005a) (Eq. (1)).

$$\text{Mean thickness [m]} = 50 * (\text{area [km}^2])^{0.2} \quad , \tag{1}$$

Rock glaciers do not contain 100% ice by definition, and the ice content within them is spatially heterogeneous. Therefore, we used the worldwide estimates for ice content within rock glaciers ranges (40% - 60%) to further calculate their lower, mean, and upper ice volume (Hausmann *et al.*, 2012; Krainer and Ribis, 2012; Rangecroft *et al.*, 2015; Jones *et al.*, 2018b; Wagner *et al.*, 2021), then converted them to the WVEQ by assuming the ice density conversion factor of 0.9 g cm^{-3} (≡900 kg m^{-3}) (Paterson, 1994; Jones *et al.*, 2018b).

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Ice volumes were calculated from the following Eq (2):

$$V = A * \sum H \quad , \tag{2}$$

where V represents ice volume, A is the glacier surface area from the Second Glacier Inventory Dataset of China (Liu *et al.*, 2019), and H is the ice thicknesses derived from GlabTop2 (Linsbauer *et al.*, 2009). Finally, we assumed a 100% ice content by volume and applied the above ice density conversion factor to calculate the water equivalent volume of the ice glacier.

3.3 Permafrost probability distribution

The binary logistic regression model has been found appropriate to calculate the probability of permafrost distribution and has been applied in several studies worldwide (Sattler *et al.*, 2016; Deluigi *et al.*, 2017; Baral *et al.*,2019; Hassan *et al.*,2021). We assumed that rock glaciers are indirect indicators of permafrost and use their inventory classified by activity status as the dependent variable, as well as used spatially distributed local topo-climatic data, i.e., the longitude, latitude, altitude, MAGT, mean annual precipitation, slope as the independent variables. The model was then trained to evaluate the correlation between the indicators.

With the support of SPSS 27.0 software, the progressive forward method (LR) was used to conduct correlation analysis and binary Logistic regression analysis of topo-climatic data. Based on the analysis results, a model for predicting the distribution probability of permafrost in GKLRJ was established.

A logistic regression model can be formulated as Eq. (3):

$$P(Y = 1) = \frac{1}{1+e^{-(\beta_0+\sum \beta_n X_n)}} \quad , \tag{3}$$

where $P(Y = 1)$ is the probability of outcome Y taking the value 1, β_0 is the intercept, and β_n is the regression coefficient of the independent variable X_n and is considered a predictor for the outcome Y. e is the base of the natural logarithm (Hassan et al., 2021).

The precipitation data (Du and Yi, 2019) and the MAGT data (Ran *et al.,*2020) we used both in the year 2015 with a spatial resolution of 1 km. All datasets were resampled to the same spatial resolution of ~30 m by ArcGIS 10.7 before the analysis, and the Zonal Statistic function was used to extract the values within rock glaciers' extent.

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4 Results

4.1 Rock glaciers inventory and distribution

4.1.1 Landform types and distribution

As shown in Table 2, 5053 rock glaciers were identified in GKLRJ, covering an area of 428.71 km^2. About 51% of rock glaciers were categorised as "virtual certainty" due to the snow coverage, and nearly 81% of rock glaciers have a Certainty Index higher than 10. The predominant dynamic type of landforms in the inventory was intact (4378, 83.64%), and the genesis type was talus-derived (4155, 82.23%). Most of these, 3548 (70.22%) were classified as 'IT'. Ninety per cent of rock glaciers are located between 4800 and 5400 m a.s.l., with a mean altitude of 5123 m a.s.l., and IDs are distributed generally higher than other types (Table.2).

Table 2: General mean characteristics of rock glaciers in GKLRJ

Region	RG Type	RG Numbers	RG area (km^2)	Altitude (m)	Length (m)	Width (m)	Slope range (°)	MEF (m)
	Intact debris	68	10.65	5185	648	256	36.44	5093
	Intact talus	412	17.84	5173	211	253	28.01	5128
	Relict debris	22	1.67	5203	364	250	33.17	5147
R1	Relict talus	248	9.66	5136	189	207	26.50	5098
	Lobate-shaped	401	15.58	5171	127	307	26.02	5137
	Tongue-shaped	349	24.24	5153	387	160	31.19	5091
	All	750	39.82	5163	248	238	28.42	5116
	Intact debris	627	99.50	5189	637	293	36.54	5100
	Intact talus	2666	206.37	5123	292	342	31.25	5066
	Relict debris	33	6.37	4979	819	271	37.32	4804
R2	Relict talus	203	19.82	4976	368	377	30.57	4898
	Lobate-shaped	1608	138.17	5121	201	485	30.69	5071
	Tongue-shaped	1921	193.89	5127	497	210	33.48	5050
	All	3529	332.06	5125	362	335	32.21	5060
	Intact debris	135	16.08	4987	505	273	35.74	4097
	Intact talus	470	25.14	4953	256	270	29.35	4902
	Relict debris	13	3.02	4841	869	276	38.87	4707
R3	Relict talus	156	12.59	4698	328	339	32.99	4633
	Lobate-shaped	308	19.56	4895	173	422	30.00	4849
	Tongue-shaped	466	37.27	4912	424	194	32.26	4843
	All	774	56.83	4905	324	285	31.35	4845
All	Intact	4378	375.58	5115	342	316	31.72	5054

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Relict	675	53.14	4975	324	295	30.21	4910
Debris	898	137.29	5146	621	285	36.40	5055
Talus	4155	291.41	5086	278	319	30.46	5031
Intact debris	830	126.23	5156	616	287	36.41	5068
Intact talus	3548	249.37	5106	277	323	30.62	5051
Relict debris	68	11.06	5025	681	265	36.27	4896
Relict talus	607	42.07	4970	284	298	29.53	4912
Lobate-shaped	2317	173.31	5100	185	446	29.79	5053
Tongue-shaped	2736	255.4	5094	470	201	32.98	5020
Total	5053	428.71	5097	339	313	31.52	5035

* RG = rock glacier; MEF = the mean elevation of the front.

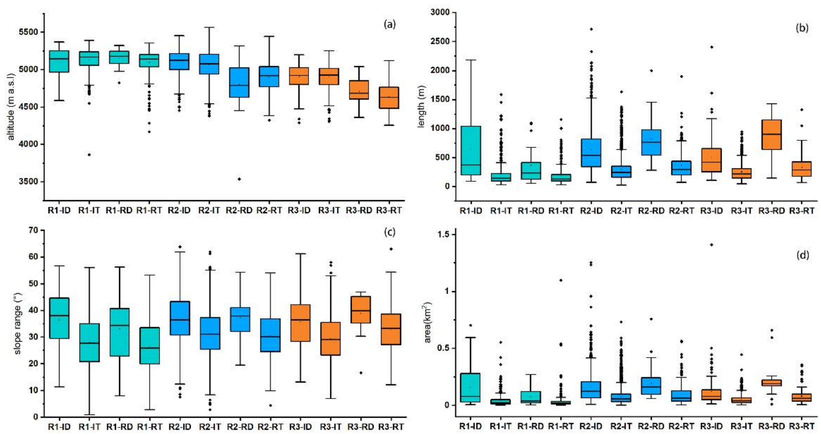

Figure 3: Box plots illustrating the distributional characteristics of four dynamic and origin types rock glaciers in R1, R2, and R3: (a) mean altitude (m a.s.l.), (b) area (km^2), (c) range in the gradient of the slope (∘), and (d) length (m).

We analysed the characteristics of rock glaciers regionally and GKLRJ-wide. Fig.3(a) shows that the mean altitude decreases gradually from R1 to R3, and IDs are located at higher mean altitudes than other types in R2 (5189 m a.s.l.) and R3 (4987 m a.s.l.), while the RDs in R1 (5203 m a.s.l) are higher. Across GKLRJ, debris-derived rock glaciers are generally longer than talus-derived, and RDs are usually the longest (fig.3(b)). This pattern is also reflected in R2 (819 m) and R3 (869 m), except in R1 that IDs (648 m) have the longest mean length. As shown in fig.3(c), debris-derived rock glaciers have a large slope range regionally. However, the largest type in each sub-region is different, which in R2 (37.32°) and R3 (38.87°) are the RDs, and in R1 (36.44°) are IDs. Moreover, it could be seen in fig.3(d) that the debris-

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derived rock glaciers all have a larger size than the talus-derived in sub-regions, although the sum areas of IDs are greater.

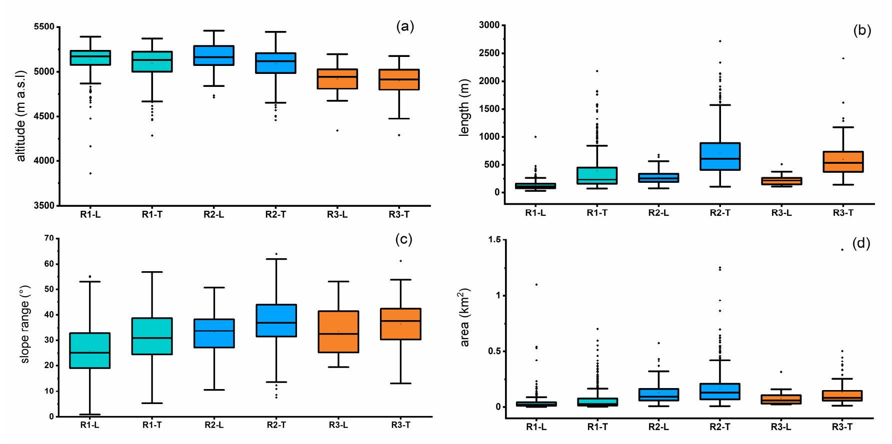
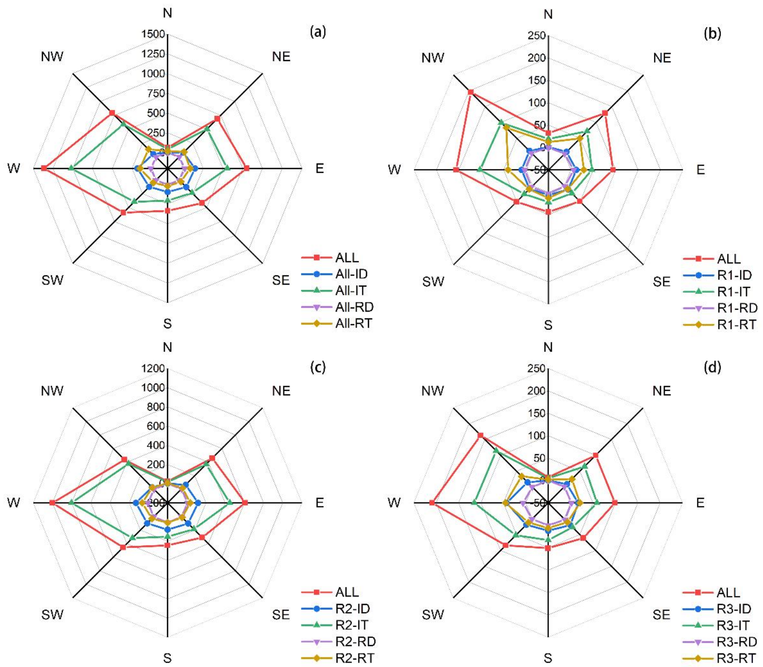


Figure 4: Box plots illustrating the distributional characteristics of two geometry types of rock glaciers in R1, R2, and R3: (a) mean altitude (m a.s.l.), (b) area (km^2), (c) range in the gradient of the slope (◦), and (d) length (m).

As shown in fig.4, the lobated-shaped rock glaciers located at higher altitudes overall, and generally have a longer mean width. While tongue-shaped rock glaciers regionally have longer lengths, larger areas, and more extensive ranges in the slope gradient. Except in R1, the tongue-shaped rock glaciers are located at higher altitudes than the lobate-shaped. Furthermore, the mean length of the tongue-shaped rock glaciers (497 m) and the mean width of the lobate-shaped rock glaciers (485 m) in R2 are significantly higher than the mean level of other sub-regions (Table 1).

4.1.2 Abundance in different aspects



210 **Figure 5: Analysis of abundances for different activity state of rock glaciers. The number of rock glaciers for each aspect on the four radar plots is shown as a percentage (%). Note: ID is the intact debris-derived rock glacier, IT is the intact talus-derived rock glacier, RD is the relict debris-derived rock glacier, and RT is the relict talus-derived rock glacier.**

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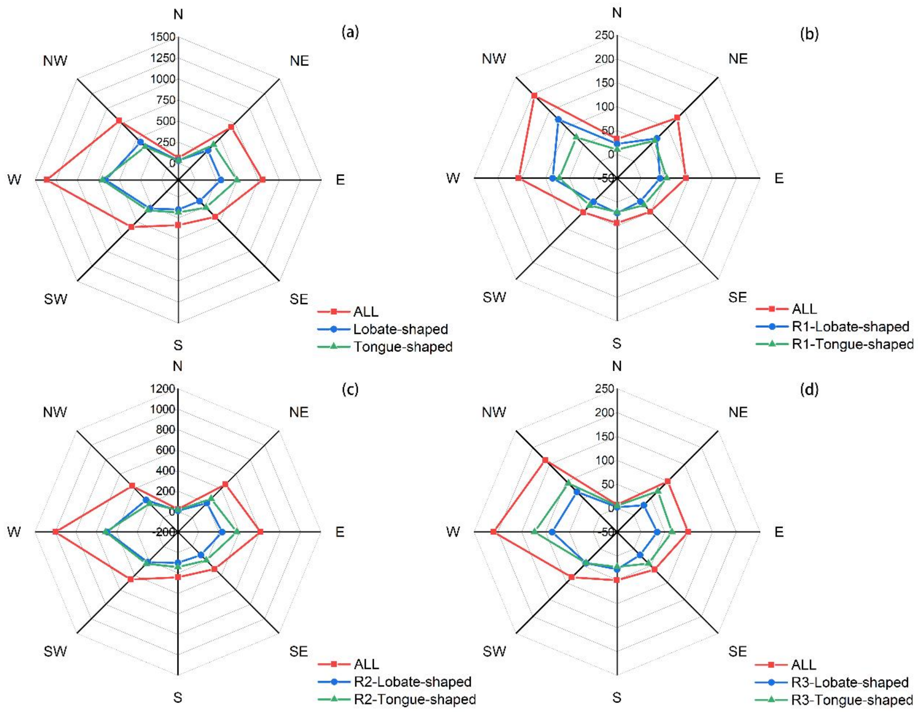

Figure 6: Analysis of abundances for different geometrical types of rock glacier. The number of rock glaciers for each aspect on the four radar plots is shown as a percentage (%).

Rock glaciers in GKLRJ are mainly distributed on the west-facing slope (W, 26.97%; NW, 15.69%; SW, 11.68%), with some distributed on the east-facing slope (E,15.85%; NE, 13.62%), and least distributed on north-facing (1.23%) slope. As shown in fig.5(a), ITs are prominently distributed on the W aspect (29%) in GKLRJ-wide, this distribution is nearly consistent in R2. While in R1 and R3, the proportions in the NW aspect increase significantly but are still less than in the W aspect. Geometry classification of observed landforms shows that tongue-shaped rock glaciers are mainly situated on the W aspect in GKLRJ and sub-regions. While lobate-shaped rock glaciers are not quite the same, such as the landforms in R1 are more concentrated on the NW aspect (fig.6).

4.1.3 Principal component analysis result

As shown in Table 3, there were significant correlations among all environmental factors ($P \leqslant 0.05$), moderate negative correlation (-0.6 < the correlation coefficient < -0.4) between the altitude of the rock glacier distributed and the precipitation, and between MAGT and the precipitation.

Table 3: Correlation matrix of rock glacier variables.

	Altitude	Mean Slope	Mean Aspect	Area	Precipitation	MAGT	PISR
Altitude	**1**	**-0.036****	**-0.026***	**-0.057****	**-0.462****	**-0.065****	**0.213****
Mean Slope	**-0.036****	**1**	**0.076****	**-0.269****	**-0.042****	**0.096****	**-0.217****
Mean Aspect	**-0.026***	**0.076****	**1**	**-0.062****	**0.024***	**-0.090****	**0.030***
Area	**-0.057****	**-0.269****	**-0.062****	**1**	**0.057****	**-0.096****	**0.052****
Precipitation	**-0.462****	**-0.042****	**0.024***	**0.057****	**1**	**-0.413****	**-0.067****
MAGT	**-0.065****	**0.096****	**-0.090****	**-0.096****	**-0.413****	**1**	**-0.184****
PISR	**0.213****	**-0.217****	**0.030***	**0.052****	**-0.067****	**-0.184****	**1**

Note: correlations in bold are significant. ∗ indicates a $P \leqslant 0.05$. ∗∗ indicates a $P \leqslant 0.01$.

4.2 Water equivalent volumes

The mean ice thickness of intact rock glaciers in GKLRJ has been estimated to be about 28.48m. As illustrated in Table 4, the WVEQ storage is between 4.55 and 6.82 km^3, among which R2 stores about 80% of the water in GKLRJ about 3.73-5.59 km^3. R1 and R3 store only 0.34-0.51 km^3 and 0.48-0.72 km^3.

Table 4: GKLRJ and regional area (km^2) and associated WVEQ (km^3) for intact rock glaciers and glaciers.

Region	Intact RG area (km^2)	WVEQ (km^3)			Glacier area (km^2)	Glacier-WVEQ (km^3)	RG: Glacier WVEQ ratio
		40%	50%	60%			
All	375.58	4.55	5.69	6.82	372.61	9.29	1:1.63
1	28.48	0.34	0.43	0.51	9.42	0.19	2.26:1
2	305.87	3.73	4.66	5.59	275.95	6.6	1:1.42
3	41.22	0.48	0.60	0.72	87.24	2.51	1:4.18

According to The Second Glacial Catalogue Data Set of China (Liu *et al.*, 2012), ice glaciers in GKLRJ cover an area of about 372.32 km^2. Simulation results of the GlobTop2 model showed that the thickness of ice glaciers ranges between ~1 and ~263 m (mean = ~18 m), with total WVEQ estimated to be ~9.29 km^3. This translates to a WVEQ ratio of 1:1.63 for intact rock glaciers and glaciers, indicating that glaciers store ~1.63 times more water volume than intact rock glaciers.

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4.3 Permafrost zonal index

We selected the climate-topo factors excluding "area" ($P>0.05$) as the dependent variables of the model to fit the logistic regression model. The accuracy of the model is 88.5%.

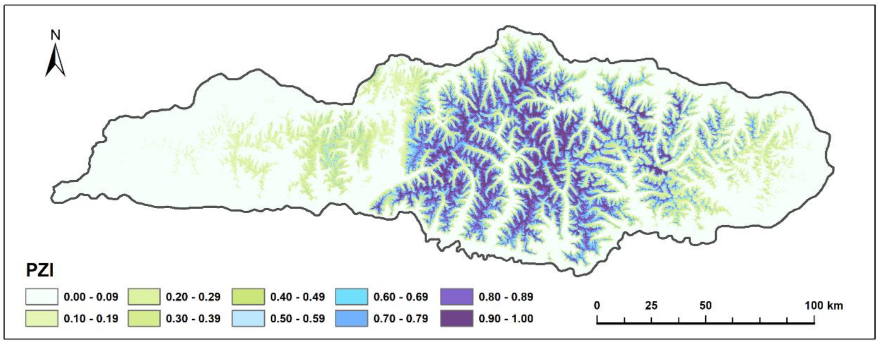

Figure 7: Probability distribution of permafrost in GKLRJ.

Based on the above model, we drew the permafrost probability distribution map (fig.7). By referring to previous study results (Baral *et al.*, 2019; Hassan *et al.*, 2021), we chose 0.5 as the critical value to classify the presence of permafrost in GKLRJ. PZI⩾0.5 indicates the permafrost presence, while PZI < 0.5 indicates the 'permafrost absence', which means the possible presence of seasonal freezing and thawing process in the area. Approximately 30% of GKLRJ (5651 km^2) distribute in the permafrost probability zone of PZI⩾0.5. The maximum area (11708 km^2; 51%) of the PZI occurred between the PZI values of 0.10 to 0.19, with the minimum elevation of 2884 m a.s.l. The minimum elevation of permafrost probability area with PZI value in the range of 0.50 ~ 0.59 is 4476 m a.s.l., and the minimum elevation of permafrost probability area with PZI value in the range of 0.89 ~ 0.99 is 4790 ~ 5860 m a.s.l., covering an area of 1521 km^2 (6.6%).

In addition, we analyzed the Receiver Operating Characteristic Curve (ROC) in SPSS with the predicted value of *P* from the regression analysis as the independent variable, and the presence or absence of permafrost indicated by rock glaciers as the dependent variable. The area under the ROC curve (AUC) was calculated to be 0.85. According to the characteristics of the ROC curve, there is some accuracy when 0.7<AUC<0.9, indicating that the independent variables are closely related to the dependent variables. The model could be used for the probability prediction of permafrost distribution in GKLRJ.

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5 Discussion

5.1 Controlling factors on rock glaciers

The number of rock glaciers in GKLRJ increased from west to east and then decreased, with more than half concentrated in the central part (R2). This is more complex than the distribution pattern in the mountains surrounding the TP, such as the Gangdise Mountains (Zhang *et al.*, 2022), Nepalese Himalaya (Jones *et al.*, 2018b), and Daxue Shan (Ran and Liu, 2018), and may be related to the unique location of GKLRJ in the transition belt between the temperate semi-arid and humid regions as well as the regional lithologic environment. The development of rock glaciers is a complex function of responses to air temperature, insolation, wind, and seasonal precipitation over a considerable period (50–200 years) (Humlum, 1998), with the altitude of MAAT 0°C and the equilibrium line on glaciers (ELA) respectively forming the lower and upper boundaries of the cryogenic belt where they developed (Humlum, 1988; Brenning, 2005a; Rangecroft *et al.*, 2015, 2016; Jones, 2018b). In the humid region, abundant precipitation accelerates glaciation and reduces the vertical extension of the cryogenic belt, resulting in a smaller niche with fewer rock glaciers developed. In the drier semi-arid and arid regions, the cryogenic belt extent became larger due to the reduced precipitation and elevated ELA, which will be more conducive to rock glacier development (Barsch, 1998). For example, in the semi-arid western part of GKLRJ, the number of rock glaciers increases with more precipitation, in line with the distribution pattern of the Gangdise Mountains located in the west (Zhang *et al.*, 2022). While in the humid eastern part of GKLRJ, the number of rock glaciers gradually decreases with increasing temperature and humidity, showing the same distribution pattern as those of Daxue Shan and Nepalese Himalaya (Ran and Liu, 2018; Jones *et al.*, 2018b). Therefore, in the central transition region with the best temperature and precipitation combination conditions in the middle of GKLRJ, rock glaciers are the most densely distributed. Furthermore, results based on quantitative calculations also verify the climate influence on the development of rock glaciers (data from Liu *et al.*, 2019; Du and Yi, 2019). The areas of the cryogenic belt in R1, R2, and R3 are 39.82 km^2, 332.06 km^2, and 56.83 km^2, which are consistent with the pattern of rock glacier abundance in each region.

If other conditions are favourable, rock glaciers can develop in almost any rock type, which breaks down to particles of at least a few cubic centimetres (cm^3) (Barsch, 1996). Compared with schist, shale, and other lithologies that mainly produce finer or platy debris, granite, gneiss, sandstone, and limestone,

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which produce boulders or blocky debris, are more conducive to ventilation and cooling within rock glaciers and help to generate and preserve an ice core in rock glaciers (Wahrhaftig and Cox, 1959; Haeberli *et al.*, 2006). In addition, the areas dominated by metasedimentary bedrock are more conducive to the storage and freezing of surface water and can enhance freezing and thawing (Johnson *et al.*, 2007). In GKLRJ, granite (including granodiorite)) is the dominant lithology of rock glaciers debris (60%), followed by volcanic breccia (18.5%) and quartz sandstone (16%). Among them, the average areas of rock glaciers developed on neutral magmatic bedrock (e.g. granite, granodiorite, andesite) are relatively larger. Therefore, compared to R1, where sandstone, shale and slate are widely distributed, R2 and R3, which have larger areas of granite, andesite and quartz sandstone distributions, are more conducive to rock glacier development.

With the west to the east extension of the Gangdise Mountains, the elevation of rock glaciers gradually decreases, which may be the result of a combination of topographical and climatic influences (Zhang *et al.*, 2022). On the one hand, regional topographic conditions will limit the highest elevation of rock glacier development. On the other hand, the stronger negative correlation between altitude and mean annual precipitation in GKLRJ suggests that precipitation mainly controls the elevation at that rock glaciers develop, with increased precipitation encouraging rock glaciers to develop at lower elevations. Therefore, from the main part of Gangdise Mountains to the eastern extension part (GKLRJ) with the continuous downward terrain and the continuously increased precipitation, the mean altitude of rock glaciers development gradually decreased.

Unlike most previous studies (Charbonneau and Smith, 2018; Pandey, 2019; Magori et al., 2020), rock glaciers were more concentrated on west-facing and east-facing slopes rather than the shaded slopes of mountain ranges (e.g. northern slopes in the northern hemisphere) in GKLRJ. Further factor analyses of elevation, mean annual precipitation, MAGT, PISR, and the area occupied by different aspects in the MAGT < 0°C regions indicated that the number of rock glaciers on the each-facing slope was only significantly correlated with the area on the each-facing slope that satisfies the condition MAGT < 0℃ (P < 0.01), with a correlation coefficient of 0.910. Thus, this indicates that the original topography significantly contributed more to the development of rock glaciers than solar radiation in GKLRJ.

Taluses were the dominant material input of rock glaciers in GKLRJ, which was strongly controlled by precipitation and topography. Previous studies have shown that with mean annual precipitation of 450 mm as the boundary, talus-derived rock glaciers mainly develop in dry and cold mountainous areas where

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precipitation is less than 450 mm (Liu *et al.*, 1995), such as the headwater of Urumqi River in the Tianshan Mountains and the Colorado Mountains in the western United States (Whalley and Matin, 1992; Dixon and Abrahams, 1992). While rock glaciers in mountainous areas with more than 450 mm annual precipitation are mainly debris-derived, such as the Alps and the Brooks Range in Alaska (Haeberli, 1985; Giardino *et al.*, 1987; Martin and Whalley, 1987; Liu *et al.*, 1995). Among them, the talus-derived rock glaciers are mostly located at the bottom of the talus slope, mainly transporting frost-shattered rock fragments derived from adjacent rock walls, while the debris-derived rock glaciers are always located under the end moraine of glaciers, mainly transporting reworked glacial debris (till) (Barsch, 1996; Lilleøren and Etzelmüller, 2011; Scotti *et al.*, 2013). Therefore, the lack of precipitation in the semi-arid region and the large-scale glacial erosional landforms in GKLRJ make a large amount of talus-derived rock glaciers develop here.

5.2 Hydrological Significance

In the Yarlung Zangbo River basin, the rapid melting of glaciers has transformed the glacial environment into periglacial environment, providing favourable conditions for the development of rock glaciers. The results show that there are 4378 intact rock glaciers in the GKLRJ, about 375.58 km^2, with a WVEQ of 3.73-5.59 km^3, and rock glaciers to glaciers WVEQ ratio of 1: 1.63. The ratio of water storage between rock glaciers and glaciers in R1, R2, and R3 is 2.26:1, 1:1.42, and 1:4.18 respectively, indicating that rock glaciers stored exceed 60% water than that of the water in glaciers, and in some regions is twice that of glaciers. This result shows the essential value of rock glaciers in GKLRJ for water storage.

Jones *et al.* (2018a) presented a near-global database that estimated the ratio of rock glacier-to-glacier WVEQ is 1:456 globally (excluding the Antarctic and Subantarctic and Greenland Periphery Randolph Glacier Inventory (RGI; Pfeffer *et al.*, 2014). The ratio in GKLRJ is much higher than most results from other regional studies worldwide (Bolch and Marchenko, 2009; Rangecroft and Anderson, 2015; Wagner *et al.*, 2021), especially in the Himalayas located in southern TP (Jones *et al.*, 2018a, 2018b, 2021). However, it is pretty similar to other arid and semi-arid regions in the world where glacier presence is limited/absent and presents spatial changes under different climatic and geomorphic environment conditions (Schrott, 1996; Brenning, 2005b; Azocar and Brenning, 2010; Millar and Westfall, 2019; Jones *et al.*, 2019b; Schaffer *et al.*, 2019). In R1, the ratio of rock glacier to glacier WVEQ is the highest of sub-regions, and it is the only region where the WVEQ of rock glaciers exceeds that of glaciers. In

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previous studies, a similar situation has occurred in the Chilean Andes between 29°and 32°S, and the estimated WVEQ ratio of rock glaciers to glaciers even reached 3:1 (Azocar and Brenning, 2010). This is mainly related to the almost complete regression of glaciers in the local arid environment. R2 is the region with the most concentrated distribution of glaciers, rock glaciers, and runoff in GKLRJ. The area of glaciers is slightly smaller than that of intact rock glaciers here, and the ratio of WVEQ between them is about 1:1.42. Under future warming conditions, this proportion is expected to gradually increase as glaciers continue to retreat and rock glaciers develop further, thus the runoff will also be affected. R3 is the unique region in GKLRJ where the area of glacier is larger than that of intact rock glaciers, and the climate which is relatively warmer and wetter could provide more favourable conditions for the development of local glaciers and make more rock glaciers into relict types.

Relict rock glaciers may also constitute 'unconfined aquifers' of significant hydrological value (Geiger *et al.*, 2014). However, our research does not include them in estimation as per Jones *et al.* (2018b). After a precipitation event, relict rock glaciers could rapidly (within hours) contribute ~20% precipitation volume to discharge, and the remaining ~80% is delayed considerably with a mean residence time of ~ seven months (Kellerer-Pirklbauer *et al.*, 2013; Winkler *et al.*, 2016; Rogger *et al.*, 2017). Therefore, it is reasonable to assume that relict rock glaciers constitute significant water stores at intermediate-term timescales (Jones *et al.*, 2019b).

Overall, our study provides the first water storage assessment of rock glaciers in the southeastern TP, reveals the potential hydrological value of rock glaciers in GKLRJ, and provides an essential reference for systematic evaluation on a global scale. At the same time, rock glaciers show greater hydrological significance and refuge potential as long-term reservoirs in arid regions with severe glaciers retreat, providing essential ideas for developing water management policies in future warming scenarios. However, more research is needed on the hydro-chemical composition of the stored water in rock glaciers and whether it can be used for irrigation and drinking.

5.3 Rock glaciers to model the permafrost probability distribution

The minimum MEF of the intact rock glaciers (4500 m) is very close to the minimum elevation in the permafrost probability zone with PZI > 0.50 (4476 m), proving that the MEF of intact rock glaciers is a good indicator of permafrost distribution. Still, this result is different from the Permafrost Zonation Index (PZI) map (fig.8(b)) (Gruber *et al.*,2012) and the map of the thermal stability of permafrost(fig.8(c)) (Ran

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et al., 2020) in R1 and R3. In R1, as shown in fig.8(a), our predicted range is significantly smaller than other studies, possibly due to differences in climatic data between ages. By raster comparison calculation in ArcGIS between the mean MAAT data from 1961 to 1990 used in the study of Gruber *et al.* (2012) and MAAT data of the Tibetan Plateau in 2015 provided by Du and Yi (2019), it was found that except for a few areas in the east part of R3, the MAAT increased significantly, especially in the west part of GKLRJ. Therefore, the difference of permafrost range in R1 was caused by the regional temperature change, and the increased temperature led to the significant reduction of the permafrost range. In R3, our results are more consistent with Gruber *et al.* (2012) but significantly smaller in eastern R3 than in Ran *et al.* (2020), which may be related to the inactive rock glaciers in the discontinuous permafrost zones. On the one hand, rock glaciers may become inactive due to the melting ice within them. On the other hand, rock glaciers may also become inactive when they extend too far and cannot receive the debris from the top (Barsch, 1996). As a result, there are more relict rock glaciers distributed in the eastern part of R3, where the climate is relatively warm and humid, vegetation cover is high, and tongue-shaped rock glaciers are more developed, resulting in lower PZI.

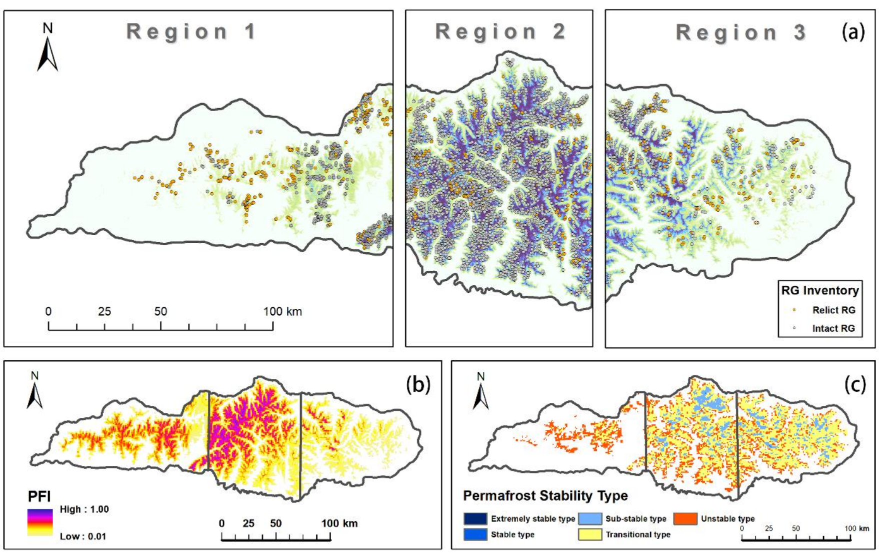

Fig 8: (a) Map of rock glaciers and permafrost probability distribution in GKLRJ, (b) Gruber's (2012) Permafrost Zonation Index (PZI) in GKLRJ, (c) Map of the thermal stability of permafrost in GKLRJ (Ran *et al.*,2020).

6 Conclusion

A total of 5053 rock glaciers covering an area of 428.71 km^2 were identified in GKLRJ, mainly distributed between 5000-5300 m a.s.l., with a mean altitude of 5097 m a.s.l. The number of rock glaciers increased and then decreased from west to east, which reflected the complex influence of temperature and precipitation combination changes in the transition belt between the semi-arid region and humid region in the plateau, indicating that cold and moderate drought conditions were more conducive to the development of rock glaciers in GKLRJ. The elevation of rock glaciers gradually decreased from west to east, which reflected the influence of regional topography and precipitation change, indicating that the increase in precipitation made it possible for rock glaciers to develop at lower elevations. Most rock glaciers in GKLRJ are distributed on the west-facing and east-facing slopes, indicating that topographic conditions played a more critical role than solar radiation in the distribution of rock glaciers here. The number of rock glaciers distributed on each slope positively correlates with the area of MAGT < 0℃ on each slope. The predominance of talus-derived rock glaciers in GKLRJ confirms the important influence of precipitation on the type of rock glaciers development. It indicates that the talus slopes formed in the former glacial environment provided richer materials for the development of rock glaciers compared to modern glacial systems. The comparison revealed that the rock glaciers inventory in GKLRJ and in Gangdise Mountains can jointly reflected the development pattern of rock glaciers in the ISM-dominated zone of the TP, revealing the critical role of precipitation in the development of rock glaciers in the semi-arid zone.

Meanwhile, rock glaciers in GKLRJ have a potential hydrological value that cannot be ignored. The WVEQ in rock glaciers is about 61% of the water that glaciers stored. This ratio may continue to increase with global warming and glaciers retreat. The prediction results based on rock glaciers inventory have a good indication for the permafrost distribution at present. The permafrost in GKLRJ shows a worsening degradation and shrinking distribution, and the change in the central and western parts is more evident than that in the eastern part. In this regard, advanced detection methods and data analysis methods such as remote sensing, InSAR, and big data should be enhanced in future research work to predict and reduce the occurrence of disasters such as landslides, avalanches, and mudslides caused by permafrost degradation.

Data availability. The data associated with this article can be found in the Supplement. These data include the Google maps of the most important areas described in this article, as well as a tabulation of the parameters of the rock glaciers found in GKLRJ.

Author contributions. ML and GL designed the research. ML performed the analysis and wrote the paper. YY and ZP provided overall supervision and contributed to the writing.

Competing interests. The authors declare that they have no conflict of interest.

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