Reply to comments by J. Müller on "Rock glaciers in the Daxue Shan, southeastern Tibetan Plateau: an inventory, their distribution, and their environmental controls"

General comments:

The authors introduce a novel rock glacier inventory of the Daxue Shan mountain range in the southeastern Tibetan Plateau. They use Google earth imagery to visually identify and map rock glaciers in the entire area. Supplementary data such as the ASTER GDEM and lithological information are implemented to assign localized geomorphometric and subsurface attributes which is used for quantitative and qualitative analysis. The methods applied in this manuscript are well established and the analysis also does not hold any surprises but it is still a novel dataset presenting the rock glacier occurrence and distribution in the southeastern Tibetan Plateau. It is overall a further step towards a global rock glacier map. I therefore recommend the publication of this manuscript after moderate revisions. Please find some remarks in the following and very specific comments in the attached pdf where I implemented some comments.

Reply: We thank Dr. J. Müller for his positive comments on our paper! We also appreciate his careful consideration and detailed comments. Our replies are highlighted in blue.

Specific comments:

Methods P5L2 You need to elaborate more on the topographic specifications of active, inactive and fossil rock glaciers. Be with your approach it is hard to identify between the three but there are certain proxies such as subsidence and vegetation which can be used to determine the state of the RG. You mention in the abstract that you also use field data for the analysis but you never mention what kind of field data you acquired and how you use it. You mention environmental controls like temperature and temperature dynamics like freeze thaw cycles numerous times in the manuscript but you never show any data. Maybe you have access to some high mountain temperature data in the area which you can show and help you with your argument. Not just the annual means as table 3 but also the annual or multiannual dynamics.

Reply: (1) Thank you very much for your constructive suggestions, we have added the relevant sentences to elaborate topographic specifications of active, inactive and fossil rock glaciers in our paper. (P5L3)

(2) Thank you for pointing out our mistaken expression and we have removed the relevant sentences "as well as upon scientific validation in the field" in the abstract.

(3) We have added data and transformed Table 3 into Figure 7 to better illustrate the freezing and thawing effect of rock glaciers in the Daxue Shan. However, there are currently only four meteorological stations. In the future, we hope to seek funding from relevant agencies and establish more meteorological stations in high altitudes.

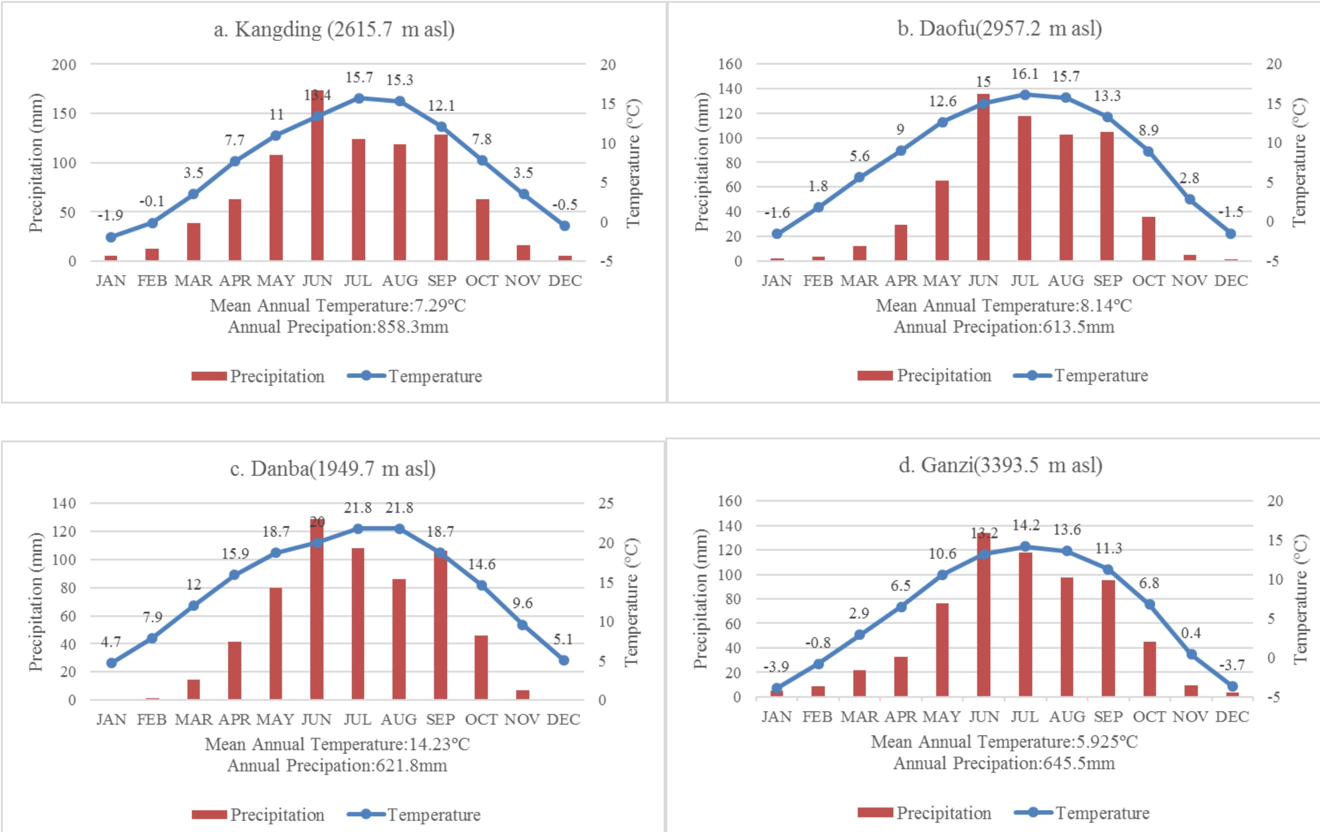

Figure 7: Climatographs for the Kangding (2,615.7 m asl, 30.03°N, 101.58°E), Daofu (2,957.2 m asl, 30.59°N, 101.07°E), Danba (1,949.7 m asl, 30.53°N, 101.53°E) and Ganzi (3,393.5 m asl, 31.37°N, 100°E) meteorological stations. Data sources: Meteorological Data Center of the China Meteorological Administration (calculated for the period 1981–2010, inclusive).

4. Results and Discussion Since you manually derived the RG geometries it would be great if you could elaborate on the accuracy of your method. Did you have several persons working on the digitization of the RGs and did they perform differently or do you have more accurate field data which you could compare to the manual mapping and are there any differences? I would suggest to refrain from using latitude and longitude to analyse RG properties since lat and long do not describe any environmental parameter but rather the regional topographical setting is more important. And thats the parameter that changes with Lat and Long. Focus more on the regional settings such as aspects, debris sources and valley/slope orientation to interpret RG properties. It would be very beneficial if you include a description of the topographical characteristics of the study site in relation to the formation and evolution of rock glaciers. This would also help to understand the spatial setting which goes with the latitudinal impact.

Reply: Thank you for your advice and it is very important, we have two persons working on the digitization of the rock glaciers and the performance is basically the same.

At present, due to the inconvenience of transportation, it is difficult for humans to go to the field to obtain field data. Therefore, we mainly identify rock glaciers through visual interpretation of google earth remote sensing images.

Your advice is very important, indeed, longitude and latitude do not describe environmental parameter. However, we use longitude and latitude not to analyze the rock glaciers properties, but to analyze the spatial distribution and aggregation state of rock glaciers from the perspective of geography. Then, we analyze the properties of rock glaciers by using other parameters other than longitude and latitude (*i.e.* the parameter that changes with longitude and latitude). As you said, regional settings are very important. Therefore, we are also concerned about aspects, debris sources and valley/slope orientation to interpret rock glaciers properties, to explore the correlation between the local topographical characteristics and the formation, evolution, spatial distribution of rock glaciers.

We have added the description sentences of the topographical characteristics "With the increase of latitude from the south to the north in the Daxue Shan, the high altitude slopes increase, there are more steep rock walls on the north faces producing debris, these topographical characteristics result in the rock glaciers altitude asl and mean gradient of slope increase with latitude." (P10L5~P10L8)

4.2.3 Lithological controls on rock glaciers. The lithological setting influences RG formation mainly by steepness and sedimentation rates contributing debris to the landforms. Please include this aspect into your elaboration and cite some references supporting the influence of lithology towards RG formation and evolution.

Reply: We have added this aspect and cited some references to support the influence of lithology towards rock glaciers formation and evolution. As shown below:

"In addition, rock glacier formation also controlled by slope and sedimentation rates contributing debris to the landforms (Müller et al., 2016). There are a large sources of sediment and sediment storages in the Daxue Shan, and are controlled by the processes occurring within this setting (Müller et al., 2014). An abundance of steep rock walls and deepened valley sides, provides catchment areas for rock glacier development, combined with intense monsoonal precipitation and tectonic activity, drives sediment transport processes and rock glacier development in the Daxue Shan." (P12L18~ P12L22)

Also you mention the existence and application of g in-situ ground truthing data but you never explain how, where and what kind of data you gathered and used. Please include this either in the method or discussion section.

Reply: Thank you for pointing out our mistaken expression and we have removed the relevant sentences "as well as upon scientific validation in the field" and "Ground truthing was only possible at a limited number of rock glacier sites within the Daxue Shan, and no fossilized glacier-derived features were visited." in the paper.

Next is the reply to the supplement to this comment: https://www.the-cryosphere-discuss.net/tc-2017-290/tc-2017-290-RC1-supplement.pdf

P2L5: All Rock glaciers move down valley. Otherwise they would move at all. Also lobate RGs are inclined and creep therefore down valley. Please rephrase...

Reply: Thanks for pointing out this. We have rewritten the relevant sentences to "As the bodies of rock glaciers are similar to moraines in that," (P2L4~P2L5)

P2L7: That's a continuum. Many Himalayan RGs develop out of moraines and it is hard to distinguish where the moraine ends and the RG begins. Please mention that.

Reply: Thanks very much for your insightful suggestion. We have added the sentence "Rock glacier is often a continuum and it is hard to distinguish where the moraine ends and the rock glacier begins."(P2L6~P2L7)

P2L12: What does block type mean? It is agreed upon that rock glaciers move due to the viscous creep of the rock-ice melange and can be described and modelled as such. see wahrhaftig & Cox 1959, Olyphant 1983. references in the written comments.

Reply: This is our misnomer and we have changed "block-type movement" to "creep movement". (P2L12)

P2L16: How are they more accurate? I would prefer advanced or powerful.

Reply: We are grateful for the suggestions, and we have changed "accurate" to "advanced". (P2L16)

P3L1: Do you mean underneath the rock glaciers or inside of the rock glacier? or altitudinal? Please rephrase.

Reply: We have rewritten the sentence is "estimations of the distribution of permafrost based on rock glaciers (Allen et al., 2008; Boeckli et al., 2012; Sattler et al., 2016; Schmid et al., 2015) ," (P3L1)

P3L10: What does minimal mean? This sentence is misleading.

Reply: We have rewritten the sentence is "However, the study of the rock glaciers of the Daxue Shan on the southeastern margins of the TP is less involved." (P3L9~P3L10)

P3L15: and natural hazards and or environmental planning/management.

Reply: We have rewritten the sentence is "It is therefore of particular importance to study the environmental controls on the rock glaciers of the Daxue Shan as an aid to the further study of the complex geographical environment, natural hazards, environmental planning and management found on the southeastern margins of the TP." (P3L15)

P5L12: reference?

Reply: The reference "A geological layer (using a geological map with a scale of 1:500,000 from the China Geological Survey)" has been added in the revised version. (P5L13~P5L14)

P7L22: Isn't this also a function of sediment supply and terrain inclination? Maybe you can discuss the impact of terrain topography and sediment/ice supply and its impact on flow velocity and RG morphology.

Reply: We are grateful for the suggestions and we have added the sentence "compared with talus-derived and lobate rock glaciers, moraine-type and tongue-shaped rock glaciers have more sediment supplies and last longer, indicating that moraine-type and tongue-shaped rock glaciers flow further than talus-derived and lobate rock glaciers." In terms of terrain inclination, terrain topography may have an impact on flow velocity and rock glacier morphology. Unfortunately, we have not found evidence of significant differences in the degree of slope of different types of rock glaciers in the Daxue Shan. (P7L23~P7L24)

P8L7: Probably be there are more steep rock walls on the north faces producing debris. Please check.

Reply: Your opinion is really right, and we have added the sentence "However, there are more steep rock walls on the north faces producing debris, north-facing (*i.e.*, N, NW and NE) slopes seem to be more favorable for the formation of lobate rock glaciers than do south-facing (*i.e.*, SW, S and SE) ones (Fig. 5)."(P8L9)

P8L21: How does the regional climate change with the latitude? I would argue that the latitude oer se isn't so important but rather the regional climate, topography and environmental setting.

Reply: Indeed, regional climate, topography and environmental setting are very important, and we have discussed them in the paper. Latitude may have little impact on the regional climate of a single small area. However, when comparing two areas in different latitudes (Daxue Shan: 30°N, Tianshan Mountains: 40°~45°N) (Wang et al., 2017; Zhu, 1992; Zhu et al., 1992), the temperature will decrease with the increase of latitude, resulting in latitude zonal differences in climate between different regions (Daxue Shan and Tianshan Mountains).

P9L1: Because there aren't so many of these W-E facing slopes?

Reply: Yes, the topographical characteristics of the Tianshan Mountains are roughly W-E in presentation, east- and west- facing slopes are less than the north- and south- slopes, these topographical characteristics are not conducive to the formation and development of rock glaciers.

P9L15: You just mentioned in line 11 that local topography and local climate are very important. Latitude and longitude have no impact on these parameters. So I'd say any correlation with these parameters is rather an expression for other local parameters influenced by e.g. topography and any interpretation including lat and long doesn't help much.

Reply: Latitude and longitude may have a little effect on other parameters of a single rock glacier; however, it can reflect the spatial distribution and aggregation characteristics of 534 rock glaciers in the Daxue Shan. It is one of the topics (titles) discussed in this paper: "their distribution", which focuses on the study of the relationship between local topography and the spatial distribution(Johnson et al., 2007) of 534 rock glaciers from the geographic space macro perspective. Therefore, we have rewritten the sentence is "In summary, the topography of the Daxue Shan is an important environmental control on the formation, development and spatial distribution of the region's rock glaciers."(P10L22~

P10L23)

P9L17: This is trivial.

Reply: Thanks for pointing out this and we have removed the relevant sentences "there is a significantly positive correlation ($p=0.01$) between rock glacier area, length and width. We also found that"

P9L22: Does this only hold true for active RGs or also for relict RGs?

Reply: In terms of statistics, it only hold true 534 rock glaciers were identified in the Daxue Shan.

P10L1: It would be very beneficial if you include a description of the topographical Characteristics somewhere in the discussion.

Reply: We have added the description sentences of the topographical characteristics "With the increase of latitude from the south to the north in the Daxue Shan, the high altitude slopes increase, there are more steep rock walls on the north faces producing debris, these topographical characteristics result in the rock glaciers altitude asl and mean gradient of slope increase with latitude." (P10L5~P10L8)

P10L7: Why? I would awesome because of temperature but further elaboration would be helpful.

Reply: We have added the further elaboration sentences "with the increase of longitude and the decrease of altitude, the closer it is to warm and humid, which kind of climatic conditions are not conducive to the formation of permafrost landforms such as rock glaciers." (P10L14~P10L15)

P10L13: This hold trues for all the slopes in the world...

Reply: It may be a common topographic feature of Daxue Shan and other regions.

P11L1: Maybe mention the global permafrost distribution maps and their take on the Daxue Shan (e.g. Gruber et al. 2012).

Reply: We have added the global permafrost distribution maps and their take on the Daxue Shan. As shown below:

"The cryosphere reacts sensitively to climate change (Gruber et al., 2017). Compared with Gruber's (2012) global permafrost zonation index map, the permafrost distribution in the Daxue Shan is highly consistent with the rock glaciers distribution (Fig. 3). Strictly controlled by the temperature decreasing with increasing altitude, further indicating the climatic controls on development of permafrost such as rock glaciers." (P11L21~P11L24)

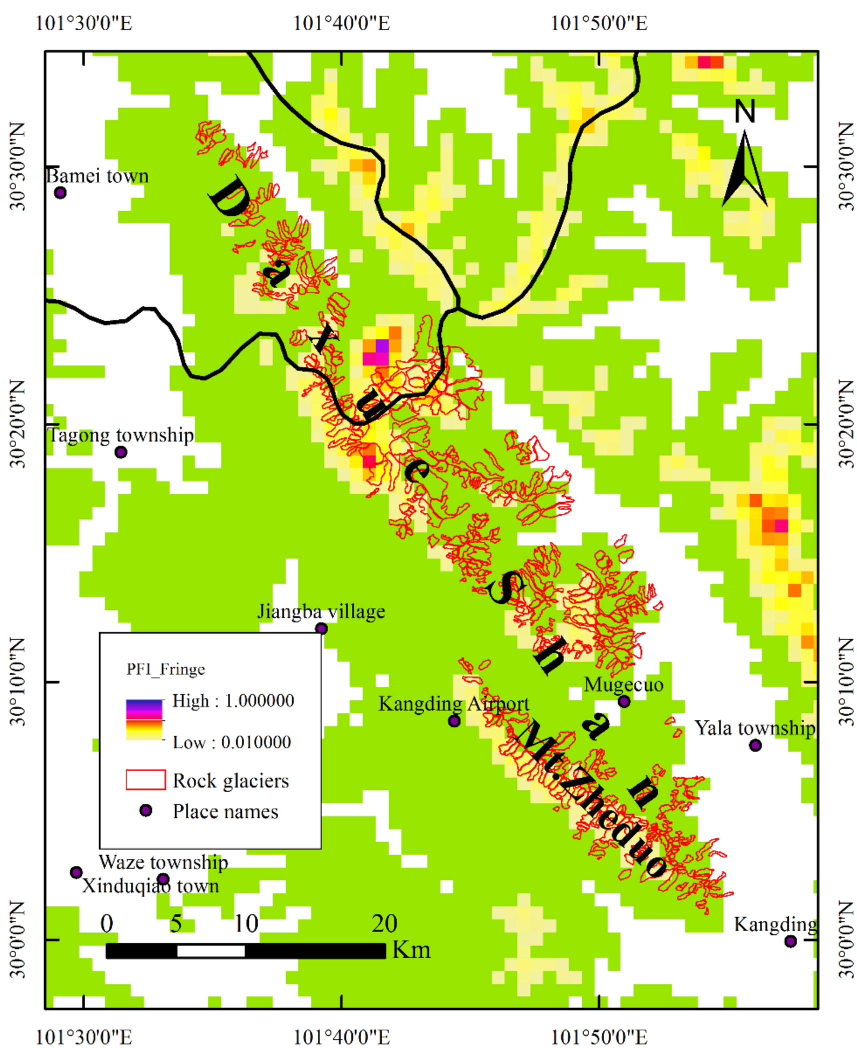

Figure 3: Spatial distribution of rock glaciers and permafrost zonation index in the Daxue Shan. The Permafrost Zonation Index (PZI) data sources: Gruber's (2012), the green area represent the fringe of uncertainty.

P12L7: Most obvious the determine the state of activity you should check InSAR or mulittemporal high resolution satellite data to derive kinematics of the rock glacier and then you have some insight in the current state of the landforms.

Reply: We are grateful for the suggestions and we have added the sentence "First, it remains to be determined whether these landforms are currently active, or whether they represent the fossilized remains of inactive rock glaciers; further analysis, when conditions permit, it therefore vital." at the beginning of the paragraph. (P13L1~P13L2)

P12L8: What kind of ground truthing? and how did you use this? Is this temperature or visual inspection or kinematics?

Reply: Thank you for pointing out our mistaken expression and we have removed the relevant sentences "Ground truthing was only possible at a limited number of rock glacier sites within the Daxue Shan, and no fossilized glacier derived features were visited."

P12L14: This should in some cases be visually applicable.

Reply: Your suggestion is very useful and we will try to use it as much as possible in future related research.

P12L16: Is it possible to quantify these uncertainties? Please say a few words on how strong and persistent these uncertainties are.

Reply: Although our visual interpretation error is very small, it is difficult to determine quantitatively. In the future research, it can be controlled by continuously adding more experts to use Google Earth for visual interpretation and field verification.

P12L21: What are the environmental controls?

Reply: The environmental controls are environmental factors that control and influence the formation and development of rock glaciers, such as the local topography, climate and lithology discussed in this paper.

P13L10: This sentence is very hard to understand. Do you mean you found SW-S-SE slopes to be more favorable for tongue shaped RGs of for RGs in general? and N facing better for lobate RGs?

Reply: Yes, SW-S-SE slopes to be more favorable for tongue shaped RGs in general, and N facing better for lobate RGs.

P13L14: You never really elaborated how these controls might influence RG evolution.

Reply: We are grateful for the suggestions. In this paper, we focus on exploring the correlation between local environmental controls and the spatial distribution of rock glaciers in order to preliminary study whether these local environmental controls promote or inhibit the formation of rock glaciers in a maritime setting. Therefore, the referee's concern is of importance for our further study. In the related research in the future, we will further explore how these controls influence rock glaciers evolution in terms of physics and chemistry mechanisms based on the above research results.

P13L17: You have also never showed data supporting this statement.

Reply: We have added the data in Figure 7 to support this statement.

P23L1: Please show these locations on one of the maps. And maybe you have some more stations in high altitudes.

Reply: Thanks for pointing out this. We have added data and transformed Table 3 into Figure 7 to better illustrate the freezing and thawing effect of rock glaciers in the Daxue Shan. However, there are currently only four meteorological stations. In the future, we hope to seek funding from relevant agencies and establish more meteorological stations in high altitudes.

P26L1: This legend does not very look nice and if you would make the polygons hollow you can show the permafrost map underneath.

Reply: We have made the polygons hollow and showed the permafrost map underneath (Figure 3).

P27L4: Please mention the actual number of the population of the different kinds of rock glacier in some table, or you can just pring the number into the boxplots.

Reply: Thanks for pointing out this. We have added the actual number of the population of the different kinds of rock glacier in the brackets of the legend (Figure 4).

P29L1: The numbers are very hard to read. Please relocate them.

Reply: We have relocated these numbers (Figure 6).

P30L1: An underlying transparent hillshade derived from SRTM would make this figure more appealing and more easily to interpret.

Reply: We are grateful for the suggestions. Figure 1 show that underlying transparent hillshade derived from SRTM in the previous part of the paper. In this figure, we directly show the correlation between the spatial distribution of rock glaciers and local lithology types through lithologic geological maps, in order to explore the impact of local lithological geological conditions on rock glaciers in the Daxue Shan.

References:

Allen, S. K., Owens, I., and Huggel, C.: A first estimate of mountain permafrost distribution in the Mount Cook region of New Zealand's southern alps, In: 9th International Conference on Permafrost, Fairbanks, Alaska,, 2008. pp. 37–42, 2008.

Boeckli, L., Brenning, A., Gruber, S., and Noetzli, J.: A statistical approach to modelling permafrost distribution in the European Alps or similar mountain ranges, Cryosphere, 6, 125-140, 2012.

Gruber, S.: Derivation and analysis of a high-resolution estimate of global permafrost zonation, Cryosphere, 6, 221-233, 2012.

Gruber, S., Fleiner, R., Guegan, E., Panday, P., Schmid, M. O., Stumm, D., Wester, P., Zhang, Y. S., and Zhao, L.: Review article: Inferring permafrost and permafrost thaw in the mountains of the Hindu Kush Himalaya region, Cryosphere, 11, 81-99, 2017.

Johnson, B. G., Thackray, G. D., and Van Kirk, R.: The effect of topography, latitude, and lithology on rock glacier distribution in the Lemhi Range, central Idaho, USA, Geomorphology, 91, 38-50, 2007.

Müller, J., Gärtner-Roer, I., Kenner, R., Thee, P., and Morche, D.: Sediment storage and transfer on a periglacial mountain slope (Corvatsch, Switzerland), Geomorphology, 218, 35-44, 2014.

Müller, J., Vieli, A., and Gartner-Roer, I.: Rock glaciers on the run - understanding rock glacier landform evolution and recent changes from numerical flow modeling, Cryosphere, 10, 2865-2886, 2016.

Sattler, K., Anderson, B., Mackintosh, A., Norton, K., and de Róiste, M.: Estimating Permafrost Distribution in the Maritime Southern Alps, New Zealand, Based on Climatic Conditions at Rock Glacier Sites, Frontiers in Earth Science, 4, 2016.

Schmid, M. O., Baral, P., Gruber, S., Shahi, S., Shrestha, T., Stumm, D., and Wester, P.: Assessment of permafrost distribution maps in the Hindu Kush Himalayan region using rock glaciers mapped in Google Earth, Cryosphere, 9, 2089-2099, 2015.

Wang, X. W., Liu, L., Zhao, L., Wu, T. H., Li, Z. Q., and Liu, G. X.: Mapping and inventorying active rock glaciers in the northern Tien Shan of China using satellite SAR interferometry, Cryosphere, 11, 997-1014, 2017.

Zhu, C.: Some problems from the slope periglacio-landform on middle Tian Shan Mountain, Mountain Research, Mountain Research, 10, 1992.

Zhu, C., Cui, Z. J., and Yao, Z.: Research on the feature of rock glaciers on the central Tian Shan Mountain, ACTA Geographica Sinica, 47, 1992.

Rock glaciers in the Daxue Shan, southeastern Tibetan Plateau: an inventory, their distribution, and their environmental controls

Zeze Ran* and Gengnian Liu

Key Laboratory for Earth Surface Processes of the Ministry of Education, College of Urban and Environmental Sciences, Peking University, Beijing, 100871 China

**Correspondence to*: Zeze Ran (ranzeze@pku.edu.cn)

Abstract. Rock glaciers are typical periglacial landforms. They can indicate the existence of permafrost, and can also shed light on the regional geomorphological and climatic conditions under which they may have developed. This article provides the first rock glacier inventory of the Daxue Shan. The inventory has been based on analyses of Google Earth imagery ~~as well as upon scientific validation in the field~~. In total, 534 rock glaciers were identified in the Daxue Shan, covering a total area of 156.35 km^2, between the altitudes of 4,200 and 4,600 m above sea level (asl). Supported by the ArcGIS and SPSS software programs, we extracted and calculated the parameters of these rock glaciers, and analyzed the characteristics of their spatial distribution within the Daxue Shan. Our inventory suggests that the lower altitudinal boundary for permafrost across the eight aspects of slopes observed in the Daxue Shan (*i.e.*, slopes facing north, northeast, east, southeast, south, southwest, west and northwest) differs significantly. The lower altitudinal permafrost boundary is ~88 m lower on eastern- rather than western-facing slopes. These results show that environmental controls (*i.e.*, topographical, climatic, lithological factors) greatly affect the formation and development of rock glaciers. This study provides important data for exploring the relation between marine-type periglacial environments and the development of rock glaciers on the southeastern Tibetan Plateau (TP). It may also highlight the characteristics typical of rock glaciers found in a maritime setting.

Keywords: rock glaciers; inventory; distribution; environmental controls; Daxue Shan

1 Introduction

The term ‘rock glacier’ was first proposed by the American scholar Capps when the investigating Kennicott Glacier in Alaska (Capps, 1910). By definition, rock glaciers consist of perennially frozen masses of ice and debris that creep downslope under the weight of gravity (Haeberli, 1985; Barsch, 1996; Haeberli et al., 2006). As the bodies of rock glaciers are similar to moraines in that, as their ice mass moves over a pore ice surface, they do not sort materials in relation to the thickness of the debris they contain. Rock glacier is often a continuum and it is hard to distinguish where the moraine ends and the rock glacier begins. Statistically, rock glaciers occupy extensive areas above the forest line in the mountainous regions of the world (Haeberli, 1985). Indeed, there are millions of rock glaciers in the world, with ~1,000 active rock glaciers in the Swiss Alps alone. The ways in which rock glaciers move can significantly influence any engineering and transportation infrastructure in regions affected by permafrost. The freeze-thaw process experienced by the ice masses within rock glaciers can exert a major impact on the hydrological cycle, and is vital to understand when reconstructing the local paleoclimate and paleoenvironment. Rock glaciers are therefore not only characterized by an advanced form of creep movement, but are also complex landforms which incorporate many of the phenomena observed in ice margins. Rock glacier research may therefore aid a more detailed and accurate understanding of the genesis of periglacial geomorphology and of the ongoing and developmental relation between rock glaciers and their local environments.

Over the last twenty years, with the rapid development of more advanced Geographical Information System (GIS), remote sensing (RS) and statistical techniques, rock glacier research has entered a new, accelerated phase. This phase has included the compilation of rock glacier inventories (*e.g.*, Sollid and Sørbel, 1992; Guglielmin and Smiraglia, 1998; Baroni et al., 2004; Perucca and Angillieri, 2008; Angillieri, 2009; Bolch and Marchenko, 2009; Azócar and Brenning, 2010; Cremonese et al., 2011; Kellerer-Pirklbauer and Kaufmann, 2012; Kellerer-Pirklbauer et al., 2012; Krainer and Ribis, 2012; Seppi et al., 2012; Bodin, 2013; Scotti et al., 2013; Bolch and Gorbunov, 2014; Falaschi et al., 2014; Colucci et al., 2016; Falaschi et al., 2016a; Falaschi et al., 2016b; Janke et al., 2017; Wang et al., 2017; Jones et al., 2018b), the mapping of their spatial distributions and their relations with environmental controls such as topography and climate (*e.g.*, Chueca, 1992; Brazier et al., 1998; Brenning, 2005; Janke, 2007; Johnson et al., 2007; Kenner and Magnusson, 2017; Onaca et al., 2017; Jones et al., 2018b), estimations of the distribution of permafrost based on rock glaciers (*e.g.*, Allen et al., 2008; Boeckli et al., 2012; Schmid et al., 2015; Sattler et al., 2016), the hydrological contribution of rock glaciers (Jones et al., 2018a; Jones et al., 2018b) and the dynamic movement of rock glaciers (*e.g.*, Haeberli et al., 2006; Liu et al., 2013; Muller et al., 2016; Wang et al., 2017). However, compared with ice glaciers, rock glaciers remain poorly described and infrequently studied because they are mixtures of rock fragments of different sizes, and therefore cannot easily be automatically mapped from RS data because they are spectrally similar to their surroundings (Brenning, 2009; Shukla et al., 2010). As a result, it is often difficult to distinguish relict rock glaciers from inactive rock glaciers that still contain ice using RS imagery (Millar and Westfall, 2008; Kenner and Magnusson, 2017).

Rock glacier research in China has, up to this point, focused principally on the Tianshan Mountains (Cui and Zhu, 1989; Qiu, 1993; Zhu et al., 1996; Wang et al., 2017). However, the study of the rock glaciers of the Daxue Shan on the southeastern margins of the TP is less involved. As this region is located in the transition zone between the TP and the Yangtze Platform, it has been, and continues to be, strongly uplifted and deformed due to the extrusion and collision of the Indian and Eurasian continental plates since the Quaternary. This region is therefore characterized by an extremely complex matric of relations between different environmental factors such as climate and geomorphology. It is therefore of particular importance to study the environmental controls on the rock glaciers of the Daxue Shan as an aid to the further study of the complex geographical environment, natural hazards, environmental planning and management found on the southeastern margins of the TP. The purpose of this study was twofold: first, to describe and map the previously undocumented rock glaciers in the Daxue Shan; and second, to complete a systematic inventory of the characteristics and distribution of, and environmental controls on, the rock glaciers of the Daxue Shan. In addition, there was an analysis and discussion of the mechanisms driving the formation, development and spatial distribution of the rock glaciers of the Daxue Shan rock glaciers in relation to different environmental controls (*i.e.*, climatic, topographical and lithological factors).

2 Study Area

The study area is situated in China's Sichuan Province between 29.956°N~30.573°N and 101.477°E~101.974°E (Fig. 1). The Daxue Shan include the famous Mt. Zheduo, which lies between the Yarlung and Dadu rivers. To the west is the uplifted eastern sector of the TP, and to the east are mountain gorges, both of which are important geographical boundaries. The region's climate is relatively warm and humid, and is strongly influenced by a southwesterly monsoonal atmospheric circulation. The topography of the Daxue Shan is characterized by the strong downcutting of high energy water courses such as those of the Minjiang and Dadu rivers, resulting in a great altitudinal range. East of the Daxue Shan is a subtropical monsoon climatic zone which is principally affected by the aforementioned southwesterly monsoonal atmospheric circulation, but also by a southeasterly monsoonal atmospheric circulation and the Westerlies, all of which transport abundant precipitation to this region. West of the Daxue Shan the subtropical monsoon and continental plateau climatic zones intersect, producing a cold-temperate climate, as well as abundant precipitation. Geologically, the Daxue Shan are located on the eastern margins of the TP, where the Songpan, Chuandian and South China tectonic blocks intersect. The Xianshuihe (Ganzi-Yushu) Fault passes to the northwest of the Daxue Shan (Zhang, 2013).

3 Methods

3.1 Rock glacier inventory, classification and database

The availability of more powerful RS tools such as Google Earth has transformed geomorphological fieldwork and has, on the whole, made the recognition of landforms in remote and poorly accessible areas both fast and easy (Slaymaker, 2001; Bolch, 2004; Kaab et al., 2005; Shukla et al., 2010). An inventory of the rock glaciers of the Daxue Shan was compiled using high-resolution Google Earth satellite imagery (for the period October 2014~November 2015). Google Earth has been previously used for rock glacier identification in the Bolivian Andes (Rangecroft et al., 2014) and the Hindu Kush-Himalayan region (Schmid et al., 2015). Google Earth contains the best available imagery for detecting rock glaciers across large spatial areas. The aerial identification and subsequent classification of rock glaciers in the Daxue Shan were supplemented with validation in the field where access permitted.

Rock glaciers are characterized by distinct flow features and structural patterns. Transversal or longitudinal flow features (ridges and furrows) are common on rock glaciers due to the deformation of their internal ice structures (Clark et al., 1998; Humlum, 2000; Haeberli et al., 2006; Berthling, 2011). Many rock glaciers also exhibit structural patterns such as steep frontal slopes and side slopes with swollen bodies. Due to the constant supply of talus or debris, the surface textures of rock glaciers are usually different from those of the surrounding slopes, and their surface slopes usually have little, or no, vegetation. Following the methodology of active, inactive and relict rock glaciers described in Onaca et al. (2017), we visually examined the landforms found in the Google Earth images and identified any rock glaciers. We mapped the distribution of rock glaciers in the study region using the ASTER GDEM program (to within a horizontal accuracy of 30 m) and the Google Earth imagery for November 2015, before marking the geographical location of each identified rock glacier and delineating its outline using Google Earth.

The topographical characteristics of the rock glaciers identified in the inventory were recorded in a GIS environment (ArcMap 10.2) and then extracted and recorded for each rock glacier; these characteristics were both qualitative and quantitative and included each rock glacier's geographical location (*i.e.*, the coordinates of its center), each rock glacier's type as determined using dynamic, genetic and geometric criteria (moraine-talus; tongue-lobate), and each rock glacier's aspect (north-facing, northeast-facing *etc.*), mean gradient of slope (°), area (km^2), length (m), width (m), altitude (m asl), debris source area (parameter) and bedrock lithology. A geological layer (using a geological map with a scale of 1:500,000 from the China Geological Survey) was added to the geographical location data for each rock glacier so that the relevant class of bedrock could be incorporated within the spatial distribution database.

Based on the main source of the mass input of debris into each rock glacier and its subsequent transport downslope, we subdivided rock glaciers into two distinct categories: talus-derived rock glaciers developing below talus slopes; and moraine-type rock glaciers evolving mainly from glaciogenic materials (Lilleøren and Etzelmüller, 2016; Onaca et al., 2017) (Fig. 2). In terms of their planar geometry, these rock glaciers could be subdivided into two types: lobate and tongue-shaped (Fig. 2). The length/width ratio was used to distinguish between lobate (length/width ratio <1) and tongue-shaped (length/width ratio >1) rock glaciers (Giardino and Vick, 1987; Martin, 1987; Barsch, 1996; Guglielmin and Smiraglia, 1998; Onaca et al., 2017). The overall aspect of each rock glacier was manually derived for each feature according to the main direction of the rock glacier flow before being recoded into eight categories which corresponded to the orientation of each rock glacier, viz. north-facing (337.5°~360°, 0°~22.5°), northeast-facing (22.5°~67.5°), east-facing (67.5°~112.5°), southeast-facing (112.5°~157.5°), south-facing (157.5°~202.5°), southwest-facing (202.5°~247.5°), west-facing (247.5°~292.5°) and northwest-facing (292.5°~337.5°).

3.2 Spatial and statistical analyses

We set the eight geographical and topographical parameters (*i.e.*, latitude, longitude, rock glacier (RG) area, length, width, altitude asl, mean gradient and aspect) for each of the rock glaciers of the Daxue Shan to an eight-dimensional random variable (*i.e.*, X_1, X_2, X_3 ... X_8). A correlation coefficient ρ_{ij} (i, j = 1, 2 ... 8) of X_i and X_j was introduced into the correlation matrix of the random dimensional vector as an eight order matrix for each element, and was denoted by R, thus:

$$R = \begin{bmatrix} \rho_{11} & \rho_{12} & \cdots & \rho_{18} \\ \rho_{21} & \rho_{22} & \cdots & \rho_{28} \\ \vdots & \vdots & \vdots & \vdots \\ \rho_{81} & \rho_{82} & \cdots & \rho_{88} \end{bmatrix}, \rho_{ij} = \frac{cov(X_i,X_j)}{\sqrt{DX_i}\sqrt{DX_j}}, cov\left(X_i,X_j\right) = E(\left(X_i - E(X_i)\right) \cdot \left(X_j - E\left(X_j\right)\right))$$

The diagonal element of the correlation matrix was 1, and the correlation matrix itself was a symmetrical matrix. We performed the statistical analysis using SPSS20® software. Correlations between the quantitative topographical variables were evaluated using Pearson correlation coefficients at a corresponding significance level of $p<0.05$.

4 Results and Discussion

4.1 Rock glacier distributions

In total, 534 rock glaciers were identified in the Daxue Shan (Fig. 3), covering an area of 156.35 km^2 (Table 1). Only 21 of them (3.93%; total area 6.96 km^2) were talus-derived rock glaciers. The other 513 (96.07%; total area 149.39 km^2) were moraine-type rock glaciers; 449 (84.08%; total area 129.01 km^2) of the rock glaciers were tongue-shaped. The remaining 85 (15.92%; total area 27.34 km^2) were lobate-shaped. Most rock glaciers in the Daxue Shan are therefore moraine-type, tongue-shaped rock glaciers. In the study area, we also found that the number of rock glaciers on the southwest-facing slopes of Mt. Zheduo was significantly higher than on the southwest-facing slopes of the southwestern and northwestern sectors of the Daxue Shan. Although these two sectors and Mt. Zheduo exhibit similar environmental trends and receive solar radiation patterns, the higher altitudes asl of the southwest-facing slopes of Mt. Zheduo lead to lower temperatures than those observed for the northwestern and southwestern sectors of the Daxue Shan. On the other hand, because the southwest-facing slopes of Mt. Zheduo are the most southwesterly of the whole mountain range, they experience higher levels of orogenic southwesterly monsoonal precipitation (snowfall). This combination of factors makes the southwest-facing slopes of Mt. Zheduo more conducive to the development of periglacial landforms such as rock glaciers.

The 534 rock glaciers are found at altitudes of between 4,200 and 4,600 m asl, with the mean altitude being 4,483 m asl. Moraine-type rock glaciers are mainly concentrated in the 4,400~4,600 m asl zone, and talus-derived rock glaciers in the 4,300~4500 m asl belt. Tongue-shaped rock glaciers are mainly concentrated in the 4,400~4,600 m asl zone, and lobate rock glaciers in the 4,450~4,600 m asl belt (Fig. 4a). We found that the asl altitudes of moraine-type rock glaciers were at least 100 m higher than for talus-derived rock glaciers, and that the lower boundaries of tongue-shaped rock glaciers were ~50 m lower than for lobate rock glaciers. The upper boundaries for all rock glacier types were ~4,600 m asl. The finding that tongue-shaped rock glaciers flow further downvalley than lobate rock glaciers was also verified by a comparative analysis between moraine-type, tongue-shaped rock glaciers (MTRG) versus moraine-type, lobate rock glaciers (MLRG), and talus-derived, tongue-shaped rock glaciers (TTRG) versus talus-derived, lobate rock glaciers (TLRG); the lower altitudinal boundary for MTRG and TTRG was ~100 m lower than for MLRG and TLRG. Figure 4b shows the range in areas covered by different types of rock glaciers. Apart from a few outliers, it can be seen that the area of most rock glacier types area is <0.5 km^2, and that, in this regard, there is no clear difference between these different rock glacier types. Figure 4c shows the range in the mean gradients of the slopes of different types of rock glaciers. Moraine-type and talus-derived rock glaciers exhibit mean gradients which are all concentrated within the 25°~40° range. However, tongue-shaped and lobate rock glaciers display a greater difference in mean gradient. Tongue-shaped rock glaciers have slopes with mean gradients which are concentrated in the 25°~40° range, whereas the mean gradients of lobate rock glaciers fall within the 30°~45° range, meaning that the upper and lower slopes of tongue-shaped rock glaciers are both ~5° lower than for lobate rock glaciers. Figure 4d displays the range in the lengths of different types of rock glaciers. Moraine-type and tongue-shaped rock glaciers are mostly 400~1100 m long, whereas talus-derived and lobate rock glaciers are mostly 300~500 m long, compared with talus-derived and lobate rock glaciers, moraine-type and tongue-shaped rock glaciers have more sediment supplies and last longer, indicating that moraine-type and tongue-shaped rock glaciers flow further than talus-derived and lobate rock glaciers.

Our dataset revealed that, apart from south-facing (6.0%) and southeast-facing (5.6%) slopes, the rock glaciers of the Daxue Shan are fairly evenly distributed on slopes with the remaining six aspects, which each aspect accounting for ~15% of the total.

Moraine-type and tongue-shaped rock glaciers are found to a similar degree on all aspects, but talus-derived and lobate rock glaciers are significantly different in their distribution. Talus-derived rock glaciers are most often southwest-facing (23.8%) and southeast-facing (23.8%); they are less commonly northeast-facing (4.76%), northwest-facing (4.76%) and west-facing (9.52%), and we identified no north-facing (0%) talus-derived rock glaciers. Lobate rock glaciers tend to be found less on south-facing (4.71%) and southeast-facing (7.06%) slopes, but more commonly on north-facing (20%) ones. We compared all our results and discovered that south-facing (*i.e.*, SW, S and SE) slopes appear more conducive to the formation of rock glaciers than do north-facing (*i.e.*, NW, N and NE) ones. However, there are more steep rock walls on the north faces producing debris, north-facing (*i.e.*, N, NW and NE) slopes seem to be more favorable for the formation of lobate rock glaciers than do south-facing (*i.e.*, SW, S and SE) ones (Fig. 5).

The mean altitude of a rock glacier's front (MAF) has often been taken to be a good approximation of the lower boundary of the discontinuous permafrost zone (*i.e.*, Scotti et al., 2013). We found a significant altitudinal difference between the lower permafrost boundaries identified on the abovementioned eight aspects as they were categorized for the Daxue Shan. For example, permafrost was assumed to be probable above 4,298 m asl on east-facing slopes, and above 4,398 m asl on west-facing slopes. The mean lower permafrost boundary was calculated as occurring at 4,361 m asl (derived from a mean value of 4,321 m asl for east-facing slopes at 4321m, and 4,409 m asl for west-facing slopes). The mean lower permafrost boundary on east-facing (shady) slopes would therefore be 88 m lower than that of west-facing (sunny) slopes (Fig. 6).

Several researchers (*e.g.*, Cui and Zhu, 1989; Zhu, 1992; Zhu et al., 1992; Liu et al., 1995) have previously identified hundreds of rock glaciers in the northern Tianshan Mountains. They found that most of the identified rock glaciers were tongue-shaped, and were located at altitudes between 3,300 and 3,900 m asl, on north-facing slopes. Most rock glaciers in the Daxue Shan are also tongue-shaped. However, the altitudes at, and the aspects on, which these rock glaciers are found differ between the Daxue and the Tianshan mountain ranges. First, in terms of altitude, the rock glaciers of the Daxue Shan are located at altitudes between 4,300 and 4,600 m asl, higher than the Tianshan rock glaciers by approximately 700~1000 m. It would be reasonable to assume, therefore, that the rock glaciers located in lower latitudes are more likely to be found at higher altitudes. Second, in terms of aspect, the rock glaciers of the Daxue Shan are more evenly distributed across all eight abovementioned aspects than are the rock glaciers of the Tianshan Mountains. This could be explained by several factors, including the differences in overall altitude, as well as in the orientation of the main massif of each mountain range. The Daxue Shan lie along an approximately NW-SE axis, whereas the Tianshan Mountains are roughly W-E in presentation. Rock glaciers are therefore less commonly found on the east- and west-facing slopes of the Tianshan. The effect of solar radiation is stronger on the south-facing slopes of the Tianshan Mountains than on its north-facing ones, meaning that conditions on these south-facing slopes are less conducive to the development of rock glaciers; most of the range's rock glaciers are therefore found on its north-facing slopes. Furthermore, when higher altitudes are reached, all aspects experience lower air temperatures, resulting in a lessening of the impact caused by the difference between air temperature and solar radiation exposure; this phenomenon is similar to that found in the Daxue Shan, and explains why rock glaciers there are fairly evenly distributed on all eight aspects. However, when altitudes are lower, the impact of solar radiation, combined with warmer air temperatures, is greater, particularly on south-facing slopes; both temperature and solar radiation are lesser on shady north-facing slopes, however, explaining the predominance of north-facing rock glaciers in the Tianshan Mountains.

4.2 Environmental controls on rock glaciers

The spatial distribution and dynamics of rock glaciers are especially dependent upon the local topography and climate (Springman et al., 2012; Delaloye et al., 2013). Analyzing local environmental factors is therefore crucial to obtaining an understanding of the formation, development and spatial distribution of rock glaciers.

4.2.1 Topographical controls on rock glaciers

We conducted a series of linear regression tests to assess the relations between the eight parameters (*i.e.*, latitude, longitude, RG area, length, width, altitude asl, mean gradient and aspect) selected for the rock glaciers of the Daxue Shan (Table 2). The results showed that ~~there is a significantly positive correlation (p=0.01) between rock glacier area, length and width. We also found that~~ latitude has a significantly positive correlation (p=0.01) with rock glacier length, width and area, indicating that latitude may affect the existence of rock glaciers in the Daxue Shan. The higher the latitude becomes, the greater are the length, width and area of rock glaciers, and the more conducive is the environment to their formation and development. The spatial distribution of the rock glaciers of the Daxue Shan is therefore related to latitude. In addition, altitude asl has a significantly positive correlation (p=0.01) between rock glacier width and area; larger-scale rock glaciers occur mainly in the higher mountains. We also found a significantly positive correlation (p=0.05) between latitude, altitude asl and mean gradient of slope, a relation which is locally determined by the topographical characteristics of the Daxue Shan. With the increase of latitude from the south to the north in the Daxue Shan, the high altitude slopes increase, there are more steep rock walls on the north faces producing debris, these topographical characteristics result in the rock glaciers altitude asl and mean gradient of slope increase with latitude. The altitudes of the mountains and their mean gradients increase with latitude along with a latitudinal decrease in air temperatures, meaning that the northern sector of the Daxue Shan has an environment which is more conducive to the formation of rock glaciers and other periglacial landforms. Likewise, there is a significantly negative correlation (p=0.01) between latitude and longitude, indicating no significant impact upon the NW-SE clusters of rock glaciers found in the Daxue Shan region. There is also a significantly negative correlation (p=0.01) between longitude and altitude, rock glacier length, width and area. The lower altitude areas to the east are less conducive to the development of rock glaciers, with the increase of longitude and the decrease of altitude, the closer it is to warm and humid, which kind of climatic conditions are not conducive to the formation of permafrost landforms such as rock glaciers. A significantly negative correlation (p=0.01) exists between rock glacier length and mean gradient of slope; the shortest rock glaciers are the talus-derived variety, and these have usually developed in steep topographical environments. Rock glacier area and aspect have a significantly negative correlation (p=0.05); the larger rock glaciers are mostly concentrated on shady slopes. On such slopes, the surfaces are less affected by solar radiation, and they also experience generally lower air temperatures, meaning that they are more conducive to the development of large rock glaciers. The fact that mean gradient of slope and aspect exhibit a significantly negative correlation (p=0.01) reflects the topographical realities of the Daxue Shan, where sunny slopes are often less steep than shady ones. In summary, the topography of the Daxue Shan is an important environmental control on the formation, development and spatial distribution of the region's rock glaciers.

In addition, the formation and development of the rock glaciers of the Daxue Shan are also strongly influenced by the landforms created by glacial erosion and deposition. The southeastern margins of the TP (where the Daxue Shan are located) are in a region of Quaternary glaciation which has been, and continues to be, strongly affected by monsoonal atmospheric circulations (Owen et al., 2005). This region possesses numerous ancient glacial relics and abundant landforms created by glacial erosion and deposition (Li and Yao, 1987). Glacial erosional landforms in particular evince a closely relation with the formation and development of talus-derived rock glaciers. Ice structures, snow layers and moraines within glaciers collapse from time to time, supplying talus to the feet of mountains. As a result of the freeze-thaw process and the effect of gravity, talus creep then forms rock glaciers. Glacial depositional landforms (*e.g.*, moraine ridges) are highly conducive to the formation and development of moraine-type rock glaciers. Moraine ridges or moraines left after the retreat of the ancient glaciers can provide significant quantities of boulders, erratic blocks, debris, sand and ground ice. In the process of downward peristalsis, rock glaciers can incorporate old moraine material as well as the debris from both sides of the moraine ridge.

4.2.2 Climatic controls on rock glaciers

The west-facing slopes of the Daxue Shan lie in the intersection between a sub-frigid monsoonal and a continental plateau climatic zone, and therefore experience a cold-temperate climate. At the Daofu meteorological station (2,957.2 m asl), mean annual precipitation (MAP) is ~613.5 mm, and mean annual temperature (MAT) is ~8.14°C (Fig. 7b). Based on an adiabatic rate of 0.65°C/100 m, we estimated the MAT at 4,354 m asl (*i.e.*, the lower permafrost boundary) to be ~-0.94°C. The east-facing slopes of the Daxue Shan are affected by a subtropical monsoonal climatic environment, and are affected principally by a southwesterly monsoonal atmospheric circulation, but also by a southwesterly monsoonal atmospheric circulation, and by the Westerlies. These slopes therefore experience high levels of precipitation (snowfall). MAP at the Kangding meteorological station (2,615.7 m asl) reaches 858.3 mm; MAT is ~7.29 °C (Fig. 7a). We calculated the MAT at 4,342 m asl (*i.e.*, the lower permafrost boundary) to be ~-3.93°C. Here, the freeze-thaw process would be frequent (Fig. 7), meaning that the climatic environment would provide temperature and precipitation conditions highly favorable to the formation and development of rock glaciers. The cryosphere reacts sensitively to climate change (Gruber et al., 2017). Compared with Gruber's (2012) global permafrost zonation index map, the permafrost distribution in the Daxue Shan is highly consistent with the rock glaciers distribution (Fig. 3). Strictly controlled by the temperature decreasing with increasing altitude, further indicating the climatic controls on development of permafrost such as rock glaciers.

4.2.3 Lithological controls on rock glaciers

Lithology is a critical control for the supply of talus to ice- and rock-glacier surfaces (Haeberli et al., 2006). Figure 8 shows that the major exposed strata in the Daxue Shan region are composed of Tertiary monzonitic granite, consistent with the NW-SE trending Xianshuihe Fault. The surrounding mountains in this area generally consist of biotite-muscovite granite that intruded 16~13 Ma ago (Roger et al., 1995). Also located in this region is the tectonically important Zheduotang Fault, which runs through the Zheduo Valley, and is one of the most active fault systems on the TP's margins (Allen et al., 1991). It can be seen from Figure 8 that the distribution of rock masses along the Xianshuihe Fault in the Daxue Shan region is clearly controlled by this NW-SE left-lateral strike-slip fault.

In contrast to other regions (Lilleøren and Etzelmüller, 2016; Onaca et al., 2017), we found that in the Daxue Shan both moraine-type and talus-derived rock glaciers have developed in the monzogranitic areas, and that rock glacier and monzonitic granite exhibit a highly spatial correlation and interdependence. The Tertiary monzogranites of the Daxue Shan are clearly highly conducive to the formation and development of rock glaciers. This is consistent with the findings of Onaca et al. (2017) in the southern Carpathian Mountains. According to Popescu et al. (2015), rock glaciers located in granitic and granodioritic massifs are composed of larger clasts compared with those found in metamorphic massifs. Thus, the higher porosity of the substrata in granitic and granodioritic massifs allows for a significant cooling beneath the bouldery mantle because the denser cold air is trapped between the large boulders (Balch, 1900). The lithological and mineralogical characteristics which accompany the high porosity of tertiary monzogranites are therefore more favorable to the formation and development of local rock glaciers than are other lithologies. In addition, rock glacier formation also controlled by slope and sedimentation rates contributing debris to the landforms (Müller et al., 2016). There are a large sources of sediment and sediment storages in the Daxue Shan, and are controlled by the processes occurring within this setting (Müller et al., 2014). An abundance of steep rock walls and deepened valley sides, provides catchment areas for rock glacier development, combined with intense monsoonal precipitation and tectonic activity, drives sediment transport processes and rock glacier development in the Daxue Shan.

4.3 Ideas for future research

First, it remains to be determined whether these landforms are currently active, or whether they represent the fossilized remains of inactive rock glaciers; further analysis, when conditions permit, it therefore vital. ~~Ground truthing was only possible at a limited number of rock glacier sites within the Daxue Shan, and no fossilized glacier-derived features were visited.~~ In addition, further in situ observations would be useful to constrain methods of rock glacier identification and increase accuracy when building rock glacier inventories; such fieldwork would also supplement results rendered by the Digital Elevation Model (DEM) we used to determine the altitude and aspect of each rock glacier, and which we set to a 30 m spatial resolution. Further, a higher resolution DEM paired with in situ climate datasets would provide a more accurate representation of the distribution of the rock glaciers of the Daxue Shan. Due to the limitations imposed by the 30 m spatial resolution and the uncertainties inherent in any artificial visual identification, we may have failed to identify all the rock glaciers of the Daxue Shan. These uncertainties explain why we chose to adopt a range of values rather than exact numerical figures during our statistical analyses of the formation and development of the rock glaciers of the Daxue Shan as controlled by local environmental factors.

5 Conclusions

Rock glaciers are widespread in the Daxue Shan; of these, moraine-type rock glaciers cover the largest area. The occurrence and characteristics of these rock glaciers can mostly be explained by local environmental controls.

In total, 534 rock glaciers were identified in the Daxue Shan, covering a total area of 156.35 km^2. Moraine-type and tongue-shaped rock glaciers accounted for the vast majority of these 534 rock glaciers. The altitudes at which moraine-type rock glaciers are found (*i.e.*, 4,400~4,600 m asl) are at least 100 m higher than for talus-derived rock glaciers (*i.e.*, 4,300~4,500 m asl). Further, the lower altitudinal limit of tongue-shaped rock glaciers is ~50 m lower than for lobate rock glaciers, although the upper altitudinal limit for both these types of rock glacier is ~4,600 m asl. Except for a few outliers, the area of each type of rock glacier is no greater than 0.5 km^2. There is no significant difference between moraine-type and talus-derived rock glaciers in terms of the mean gradients of the slopes upon which the glaciers are found (*i.e.*, they are all clustered within the 25~40° range), but the upper and lower mean slope gradients of tongue-shaped rock glaciers (25° and 40°, respectively) are

~5° lower than for lobate rock glaciers (30° and 45°, respectively). Moraine-type and tongue-shaped rock glaciers are longer (*i.e.*, 400~1100 m) than talus-derived and lobate rock glaciers (*i.e.*, 300~500 m). We found south-facing (*i.e.*, SW, S and SE) slopes more conducive to the formation of rock glaciers than north-facing (*i.e.*, NW, N and NE) ones, while north-facing (*i.e.*, N, NW and NE) slopes appeared more favorable to the formation of lobate rock glaciers than did south-facing (*i.e.*, SW, S and SE) ones. The mean regional lowest altitudinal limit of rock glaciers is 4,361 m asl, an altitude which was taken to indicate the local permafrost's mean lower boundary. On east-facing slopes, the permafrost's lower boundary can therefore reasonably be assumed to be 88 m lower than on west-facing slopes.

Environmental controls (*i.e.*, topographical, climatic and lithological factors) play a very important role in the formation and development of the rock glaciers of the Daxue Shan. The correlation matrix of rock glacier parameters indicates that the formation of rock glaciers is closely related to local topographical parameters. The local climatic environment leads to a frequent freeze-thaw process within these rock glaciers, a process which is also beneficial to their formation and development. Tertiary monzonitic granite, with its large clastic and highly porous characteristics, is more sensitive than other lithological components to the freeze-thaw process, and continuous weathering of this monzogranitic substratum thus provides the ideal raw material for the rock glaciers of the Daxue Shan.

Data availability

The data associated with this article can be found in the Supplement. These data include 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 the Daxue Shan.

Competing interests

The authors declare no competing interests, financial or otherwise.

Acknowledgements

This work was funded by the National Natural Science Foundation of China (Grant Nos. 41230743 and 41371082). We should like to express our appreciation to the people who have revised this article and for the great interest they have taken in improving it.

References

Allen, C. R., Luo, Z. L., Qian, H., Wen, X. Z., Zhou, H. W., and Huang, W. S.: Field-Study of a Highly-Active Fault Zone - the Xianshuihe Fault of Southwestern China, Geological Society of America Bulletin, 103, 1178-1199, 1991.

Allen, S. K., Owens, I., and Huggel, C.: A first estimate of mountain permafrost distribution in the Mount Cook region of New Zealand's southern alps, In: 9th International Conference on Permafrost, Fairbanks, Alaska, pp. 37–42, 2008.

Azócar, G. F. and Brenning, A.: Hydrological and geomorphological significance of rock glaciers in the dry Andes, Chile (27°-33°S), Permafrost and Periglacial Processes, 21, 42-53, 2010.

Balch, E. S.: Glacières or Freezing Caverns. Allen, Lane & Scott, Philadelphia (140 p). 1900.

Baroni, C., Carton, A., and Seppi, R.: Distribution and behaviour of rock glaciers in the Adamello–Presanella Massif (Italian Alps), Permafrost and Periglacial Processes, 15, 243-259, 2004.

Barsch, D.: Rockglaciers, 16, 1996.

Berthling, I.: Beyond confusion: Rock glaciers as cryo-conditioned landforms, Geomorphology, 131, 98-106, 2011.

Bodin, X.: Present status and development of rock glacier complexes in south-faced valleys (45°N, French Alps), Geogr Fis Din Quat, 36, 27-38, 2013.

Boeckli, L., Brenning, A., Gruber, S., and Noetzli, J.: A statistical approach to modelling permafrost distribution in the European Alps or similar mountain ranges, Cryosphere, 6, 125-140, 2012.

Bolch, T.: Using ASTER and SRTM DEMs for studying glaciers and rock glaciers in northern Tien Shan, In: Proceedings Part I of the Conference "Theoretical and applied problems of geography on a boundary of centuries", Almaty, Kasakhstan, 254–258, 2004.

Bolch, T. and Gorbunov, A. P.: Characteristics and Origin of Rock Glaciers in Northern Tien Shan (Kazakhstan/Kyrgyzstan), Permafrost and Periglacial Processes, 25, 320-332, 2014.

Bolch, T. and Marchenko, S.: Significance of glaciers, rock glaciers and ice-rich permafrost in the Northern Tien Shan as water towers under climate change conditions, Proceedings of the Workshop Assessment of Snow-Glacier and Water Resources in Asia, 28-30 November 2006, Almaty, doi: 10.5167/uzh-137250, 199-211, 2009.

Brazier, V., Kirkbride, M. P., and Owens, I. F.: The relationship between climate and rock glacier distribution in the Ben Ohau Range, New Zealand, Geogr Ann A, 80a, 193-207, 1998.

Brenning, A.: Benchmarking classifiers to optimally integrate terrain analysis and multispectral remote sensing in automatic rock glacier detection, Remote Sensing of Environment, 113, 239-247, 2009.

Brenning, A.: Geomorphological, hydrological and climatic significance of rock glaciers in the Andes of Central Chile (33-35°S), Permafrost and Periglacial Processes, 16, 231-240, 2005.

Capps, S. R.: Rock glaciers in Alaska, Journal of Geology, 18, 359-375, 1910.

Chueca, J.: A Statistical Analysis of the Spatial Distribution of Rock Glaciers, Spanish Central Pyrenees, Permafrost and Periglacial Processes, 3, 261–265, 1992.

Clark, D. H., Steig, E. J., Potter, N., and Gillespie, A. R.: Genetic variability of rock glaciers, Geogr Ann A, 80a, 175-182, 1998.

Colucci, R. R., Boccali, C., Žebre, M., and Guglielmin, M.: Rock glaciers, protalus ramparts and pronival ramparts in the south-eastern Alps, Geomorphology, 269, 112-121, 2016.

Cremonese, E., Gruber, S., Phillips, M., Pogliotti, P., Boeckli, L., Noetzli, J., Suter, C., Bodin, X., Crepaz, A., Kellerer-Pirklbauer, A., Lang, K., Letey, S., Mair, V., di Cella, U. M., Ravanel, L., Scapozza, C., Seppi, R., and Zischg, A.: Brief Communication: "An inventory of permafrost evidence for the European Alps", Cryosphere, 5, 651-657, 2011.

Cui, Z. J. and Zhu, C.: The structure pattern of temperature and mechanism of the rock glaciers in Urumqi River region in Tien Shan, Chinese Sci. Bull., 34, 134-137, 1989(in Chinese).

Delaloye, R., Morard, S., Barboux, C., Abbet, D., Gruber, V., Riedo, M., and Gachet, S.: Rapidly moving rock glaciers in Mattertal, 2013.

Esper Angillieri, M. Y.: A preliminary inventory of rock glaciers at 30°S latitude, Cordillera Frontal of San Juan, Argentina, Quaternary International, 195, 151-157, 2009.

Falaschi, D., Castro, M., Masiokas, M., Tadono, T., and Ahumada, A. L.: Rock Glacier Inventory of the Valles Calchaquíes Region (~25°S), Salta, Argentina, Derived from ALOS Data, Permafrost and Periglacial Processes, 25, 69-75, 2014.

Falaschi, D., Masiokas, M., Tadono, T., and Couvreux, F.: ALOS-derived glacier and rock glacier inventory of the Volcán Domuyo region (~36°S), southernmost Central Andes, Argentina, Zeitschrift für Geomorphologie, 60, 195-208, 2016a.

Falaschi, D., Tadono, T., and Masiokas, M.: Rock glaciers in the patagonian andes: an inventory for the monte san lorenzo (cerro cochrane) massif, 47°S, Geografiska Annaler: Series A, Physical Geography, 97, 769-777, 2016b.

Giardino, J. R. and Vick, S. G.: Geologic engineering aspects of rock glaciers, 1987.

Gruber, S.: Derivation and analysis of a high-resolution estimate of global permafrost zonation, Cryosphere, 6, 221-233, 2012.

Gruber, S., Fleiner, R., Guegan, E., Panday, P., Schmid, M. O., Stumm, D., Wester, P., Zhang, Y. S., and Zhao, L.: Review article: Inferring permafrost and permafrost thaw in the mountains of the Hindu Kush Himalaya region, Cryosphere, 11, 81-99, 2017.

Guglielmin, M. and Smiraglia, C.: The rock glacier inventory of the Italian Alps. Proceedings Seventh International Conference on Permafrost, Yellowknife, Northwest Territories, Canada, 1998.

Haeberli, W.: Creep of Mountain Permafrost: Internal Structure and Flow of Alpine Rock Glaciers, 1985.

Haeberli, W., Hallet, B., Arenson, L., Elconin, R., Humlun, O., Kaab, A., Kaufmann, V., Ladanyi, B., Matsuoka, N., Springman, S., and Vonder Muhll, D.: Permafrost creep and rock glacier dynamics, Permafrost and Periglacial Processes, 17, 189-214, 2006.

Humlum, O.: The geomorphic significance of rock glaciers: estimates of rock glacier debris volumes and headwall recession rates in West Greenland, Geomorphology, 35, 41-67, 2000.

Janke, J. R.: Colorado Front Range rock glaciers: Distribution and topographic characteristics, Arct Antarct Alp Res, 39, 74-83, 2007.

Janke, J. R., Ng, S., and Bellisario, A.: An inventory and estimate of water stored in firn fields, glaciers, debris-covered glaciers, and rock glaciers in the Aconcagua River Basin, Chile, Geomorphology, 296, 142-152, 2017.

Johnson, B. G., Thackray, G. D., and Van Kirk, R.: The effect of topography, latitude, and lithology on rock glacier distribution in the Lemhi Range, central Idaho, USA, Geomorphology, 91, 38-50, 2007.

Jones, D. B., Harrison, S., Anderson, K., and Betts, R. A.: Mountain rock glaciers contain globally significant water stores, Sci Rep, 8, 2834, 2018a.

Jones, D. B., Harrison, S., Anderson, K., Selley, H. L., Wood, J. L., and Betts, R. A.: The distribution and hydrological significance of rock glaciers in the Nepalese Himalaya, Global and Planetary Change, 160, 123-142, 2018b.

Kaab, A., Huggel, C., Fischer, L., Guex, S., Paul, F., Roer, I., Salzmann, N., Schlaefli, S., Schmutz, K., Schneider, D., Strozzi, T., and Weidmann, Y.: Remote sensing of glacier- and permafrost-related hazards in high mountains: an overview, Nat Hazard Earth Sys, 5, 527-554, 2005.

Kellerer-Pirklbauer, A. and Kaufmann, V.: About the Relationship between Rock Glacier Velocity and Climate Parameters in Central Austria, Austrian Journal of Earth Sciences, 105, 94-112, 2012.

Kellerer-Pirklbauer, A., Lieb, G. K., and Kleinferchner, H.: A New Rock Glacier Inventory of the Eastern European Alps, Austrian Journal of Earth Sciences, 105, 78-93, 2012.

Kenner, R. and Magnusson, J.: Estimating the Effect of Different Influencing Factors on Rock Glacier Development in Two Regions in the Swiss Alps, Permafrost and Periglacial Processes, 28, 195-208, 2017.

Krainer, K. and Ribis, M.: A Rock Glacier Inventory of the Tyrolean Alps (Austria), Austrian Journal of Earth Sciences, 105, 32-47, 2012.

Li, S. D. and Yao, H. Q.: Preliminary Study on the Rock Glaciers in the Gongga Mt. Area, Journal of Glaciology and Geocryology, 9, 55-60, 1987(in Chinese).

Lilleøren, K. S. and Etzelmüller, B.: A regional inventory of rock glaciers and ice - cored moraines in norway, Geografiska Annaler: Series A, Physical Geography, 93, 175-191, 2016.

Liu, G. N., Xiong, H. G., Cui, Z. J., and Song, C. Q.: The morphological features and environmental condition of rock glaciers in Tianshan mountains, Scientia Geographica Sinica, 15, 1995(in Chinese).

Liu, L., Millar, C. I., Westfall, R. D., and Zebker, H. A.: Surface motion of active rock glaciers in the Sierra Nevada, California, USA: inventory and a case study using InSAR, Cryosphere, 7, 1109-1119, 2013.

Martin, H. E.: Rock glaciers. Part 1: rock glacier morphology, classification and distribution, Progress in Physical Geography, 11, 260-282, 1987.

Millar, C. I. and Westfall, R. D.: Rock glaciers and related periglacial landforms in the Sierra Nevada, CA, USA; inventory, distribution and climatic relationships, Quaternary International, 188, 90-104, 2008.

Müller, J., Gärtner-Roer, I., Kenner, R., Thee, P., and Morche, D.: Sediment storage and transfer on a periglacial mountain slope (Corvatsch, Switzerland), Geomorphology, 218, 35-44, 2014.

Müller, J., Vieli, A., and Gartner-Roer, I.: Rock glaciers on the run - understanding rock glacier landform evolution and recent changes from numerical flow modeling, Cryosphere, 10, 2865-2886, 2016.

Onaca, A., Ardelean, F., Urdea, P., and Magori, B.: Southern Carpathian rock glaciers: Inventory, distribution and environmental controlling factors, Geomorphology, 293, 391-404, 2017.

Owen, L. A., Finkel, R. C., Barnard, P. L., Haizhou, M., Asahi, K., Caffee, M. W., and Derbyshire, E.: Climatic and topographic controls on the style and timing of Late Quaternary glaciation throughout Tibet and the Himalaya defined by 10Be cosmogenic radionuclide surface exposure dating, Quaternary Science Reviews, 24, 1391-1411, 2005.

Perucca, L. and Esper Angillieri, Y.: A preliminary inventory of periglacial landforms in the Andes of La Rioja and San Juan, Argentina, at about 28°S, Quaternary International, 190, 171-179, 2008.

Popescu, R., Vespremeanu-Stroe, A., Onaca, A., and Cruceru, N.: Permafrost research in the granitic massifs of Southern Carpathians (Parang Mountains), Zeitschrift Fur Geomorphologie, 59, 1-20, 2015.

Qiu, G. Q.: Development condition of alpline permafrost in the Mt.Tianshan, Journal of Glaciology and Geocryology, 15, 96-102, 1993(in Chinese).

Rangecroft, S., Harrison, S., Anderson, K., Magrath, J., Castel, A. P., and Pacheco, P.: A First Rock Glacier Inventory for the Bolivian Andes, Permafrost and Periglacial Processes, 25, 333-343, 2014.

Roger, F., Calassou, S., Lancelot, J., Malavieille, J., Mattauer, M., Xu, Z. Q., Hao, Z. W., and Hou, L. W.: Miocene Emplacement and Deformation of the Konga-Shan Granite (Xianshui-He Fault Zone, West Sichuan, China) - Geodynamic Implications, Earth and Planetary Science Letters, 130, 201-216, 1995.

Sattler, K., Anderson, B., Mackintosh, A., Norton, K., and de Róiste, M.: Estimating Permafrost Distribution in the Maritime Southern Alps, New Zealand, Based on Climatic Conditions at Rock Glacier Sites, Frontiers in Earth Science, 4, 2016.

Schmid, M. O., Baral, P., Gruber, S., Shahi, S., Shrestha, T., Stumm, D., and Wester, P.: Assessment of permafrost distribution maps in the Hindu Kush Himalayan region using rock glaciers mapped in Google Earth, Cryosphere, 9, 2089-2099, 2015.

Scotti, R., Brardinoni, F., Alberti, S., Frattini, P., and Crosta, G. B.: A regional inventory of rock glaciers and protalus ramparts in the central Italian Alps, Geomorphology, 186, 136-149, 2013.

Seppi, R., Carton, A., Zumiani, M., Dall'Amico, M., Zampedri, G., and Rigon, R.: Inventory, Distribution and Topographic Features of Rock Glaciers in the Southern Region of the Eastern Italian Alps (Trentino), Geogr Fis Din Quat, 35, 185-197, 2012.

Shukla, A., Gupta, R. P., and Arora, M. K.: Delineation of debris-covered glacier boundaries using optical and thermal remote sensing data, Remote Sensing Letters, 1, 11-17, 2010.

Slaymaker, O.: The role of remote sensing in geomorphology and terrain analysis in the Canadian Cordillera, International Journal of Applied Earth Observation and Geoinformation, 3, 11–17, 2001.

Sollid, J. L. and Sørbel, L.: Rock Glaciers in Svalbard and Norway, Permafrost and Periglacial Processes, 3, 215–220, 1992.

Springman, S. M., Arenson, L. U., Yamamoto, Y., Maurer, H., Kos, A., Buchli, T., and Derungs, G.: Multidisciplinary Investigations on Three Rock Glaciers in the Swiss Alps: Legacies and Future Perspectives, Geogr Ann A, 94a, 215-243, 2012.

Wang, X. W., Liu, L., Zhao, L., Wu, T. H., Li, Z. Q., and Liu, G. X.: Mapping and inventorying active rock glaciers in the northern Tien Shan of China using satellite SAR interferometry, Cryosphere, 11, 997-1014, 2017.

Zhang, P. Z.: A review on active tectonics and deep crustal processes of the Western Sichuan region, eastern margin of the Tibetan Plateau, Tectonophysics, 584, 7-22, 2013.

Zhu, C.: Some problems from the slope periglacio-landform on middle Tian Shan Mountain, Mountain Research, Mountain Research, 10, 1992(in Chinese).

Zhu, C., Cui, Z. J., and Yao, Z.: Research on the feature of rock glaciers on the central Tian Shan Mountain, ACTA Geographica Sinica, 47, 1992(in Chinese).

Zhu, C., Zhang, J. X., and Cheng, P.: Rock glaciers in the Central Tianshan Mountains, China, Permafrost and Periglacial Processes, 7, 69-78, 1996.

Tables and Figures:

Table 1. Statistics for the 534 rock glaciers found in the Daxue Shan.

RG type	Number of landforms	RG area (km^2)	Altitude (m asl)	Length (m)	Width (m)	Gradient of Slope (°)	MAF (m asl)
Moraine	513	149.39	4,486	794	335	33	4,360
Talus	21	6.96	4,398	374	747	33	4,306
Tongue	449	129.01	4,477	859	283	32	4,343
Lobate	85	27.34	4,514	351	714	37	4,435
MTRG	444	128.24	4,479	862	283	33	4,344
MLRG	69	21.14	4,537	358	670	38	4,462
TTRG	5	0.77	4,343	541	252	29	4,265
TLRG	16	6.19	4,416	323	902	34	4,319
All RG	534	156.35	4,483	777	351	33	4,358

Note: RG=rock glaciers; MTRG= moraine-type and tongue-shaped rock glaciers; MLRG= moraine-type and lobate rock glaciers; TTRG=talus-derived and tongue-shaped rock glaciers; TLRG= talus-derived and lobate rock glaciers; MAF= minimum altitude of rock glacier front. Altitude of rock glacier, altitude of rock glacier front, length, width and gradient of slope are all mean values.

Table 2. Correlation matrix of rock glacier parameters; marked correlations (bold) are significant at the significance level of *p*=0.01 (**) and *p*=0.05 (*).

	Latitude	Longitude	Altitude	Length	Width	RG area	Mean slope	Aspect
Latitude	1.000	**-0.921****	**0.093***	**0.236****	**0.133****	**0.190****	**0.081***	0.001
Longitude	**-0.921****	1.000	**-0.249****	**-0.136****	**-0.118****	**-0.118****	-0.043	-0.067
Altitude	**0.093***	**-0.249****	1.000	-0.048	**0.132****	**0.112****	-0.068	0.053
Length	**0.236****	**-0.136****	-0.048	1.000	**0.127****	**0.645****	**-0.297****	-0.042
Width	**0.133****	**-0.118****	**0.132****	**0.127****	1.000	**0.731****	**0.111****	**-0.081***
RG area	**0.190****	**-0.118****	**0.112****	**0.645****	**0.731****	1.000	-0.045	**-0.118***
Mean slope	**0.081***	-0.043	-0.068	**-0.297****	**0.111****	-0.045	1.000	**-0.104****
Aspect	0.001	-0.067	0.053	-0.042	**-0.081***	**-0.118****	**-0.104****	1.000

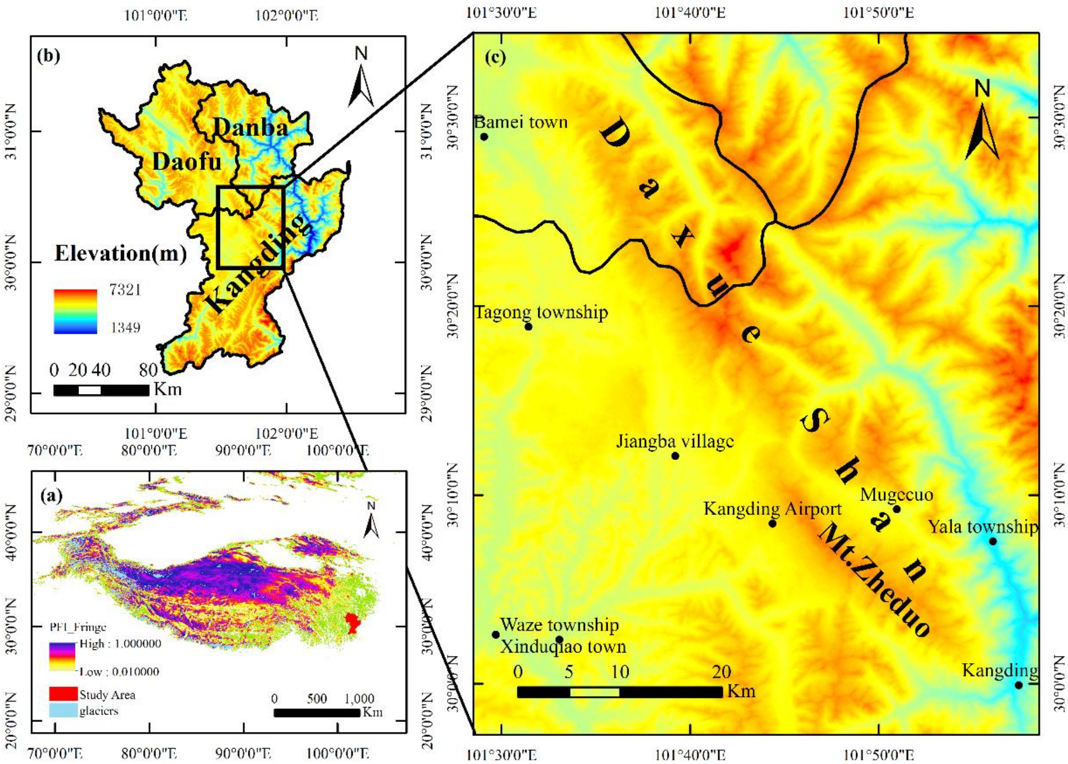

Figure 1: (a) The location of the study area in the permafrost zone of the TP. The Permafrost Zonation Index (PZI), or a corresponding map color, indicates to what degree permafrost exists only under the most favorable conditions (yellow), or nearly everywhere (blue); the map was produced using a temporal resolution of 30 arc-seconds (<1km) on a WGS84 lat/lon grid (Gruber, 2012). (b) and (c) are the geographical and topographical maps of the study area based on a spatial resolution of 30 m using ASTER-GDEM v2 software, as shown in the WGS84 coordinate system.

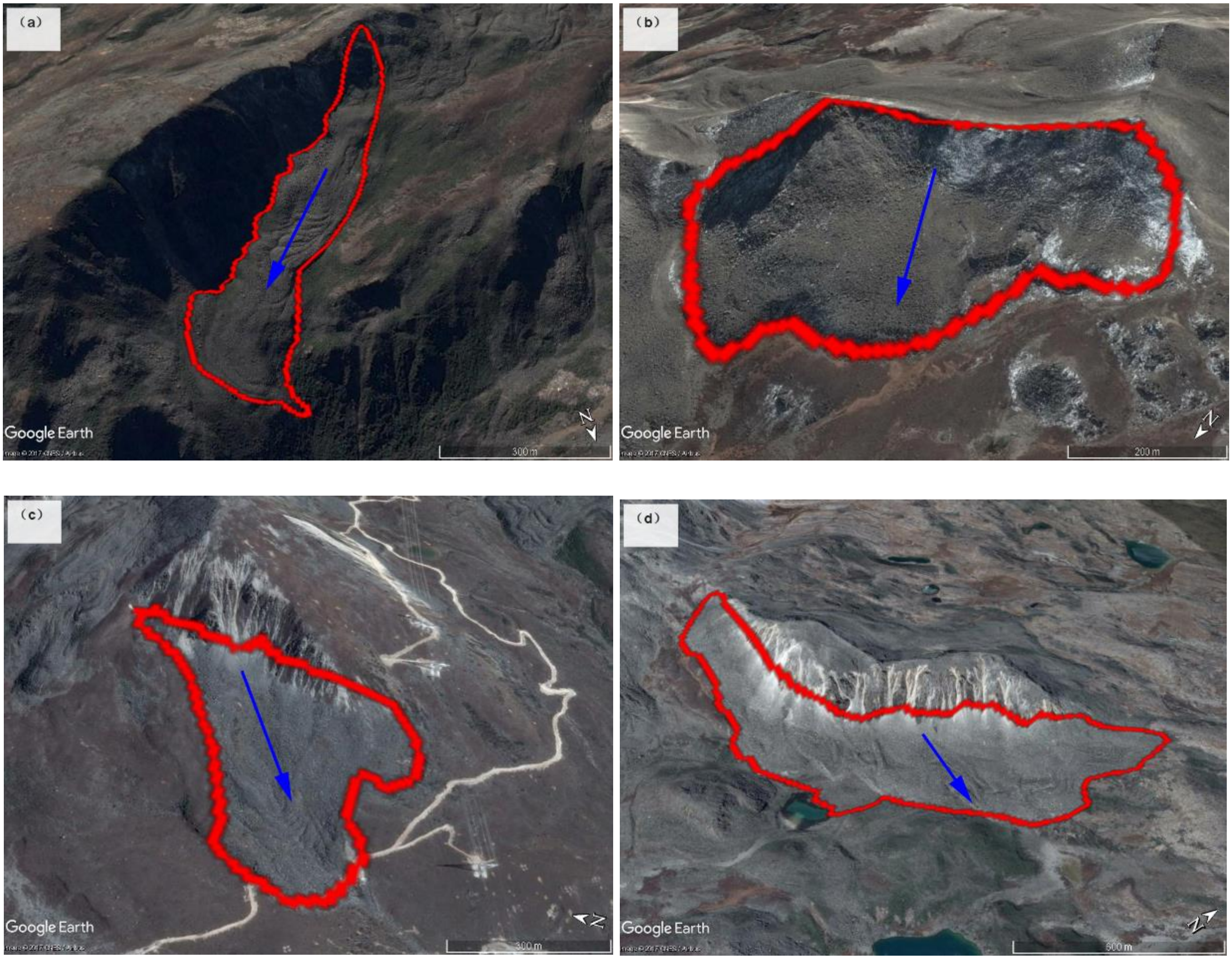

Figure 2: Examples of different types of rock glaciers in the Daxue Shan: (a) moraine-type and tongue-shaped rock glaciers (30.040597ºN, 101.911783ºE) (23rd November, 2015); (b) moraine-type and lobate rock glaciers (30.217147ºN,101.791585ºE) (15th November, 2015); (c) talus-derived and tongue-shaped rock glaciers (30.067066ºN, 101.819432ºE) (21st October, 2014); (d) talus-derived and lobate rock glaciers (30.127825ºN, 101.812158ºE) (21st October, 2014). The red lines show the outlines of the rock glaciers; the blue arrows indicate the direction of flow of the rock glaciers. Source: Google Earth.

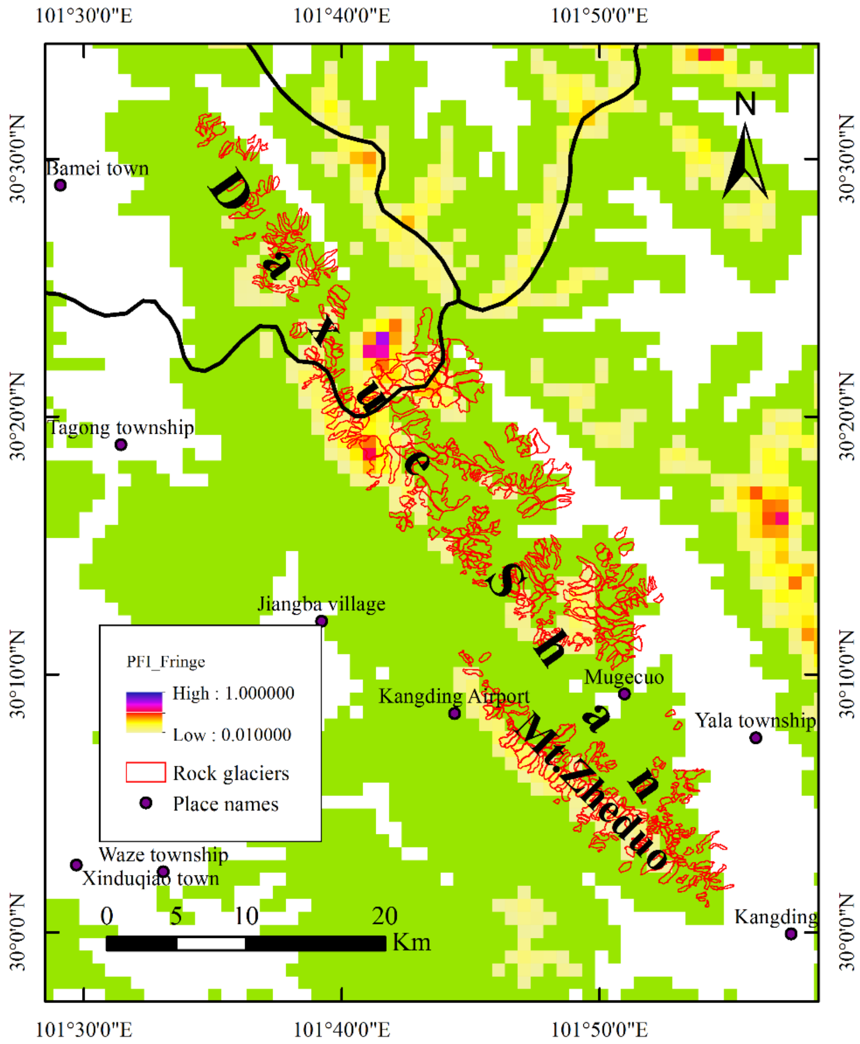

Figure 3: Spatial distribution of rock glaciers and permafrost zonation index in the Daxue Shan. The Permafrost Zonation Index (PZI) data sources: Gruber's (2012), the green area represent the fringe of uncertainty.

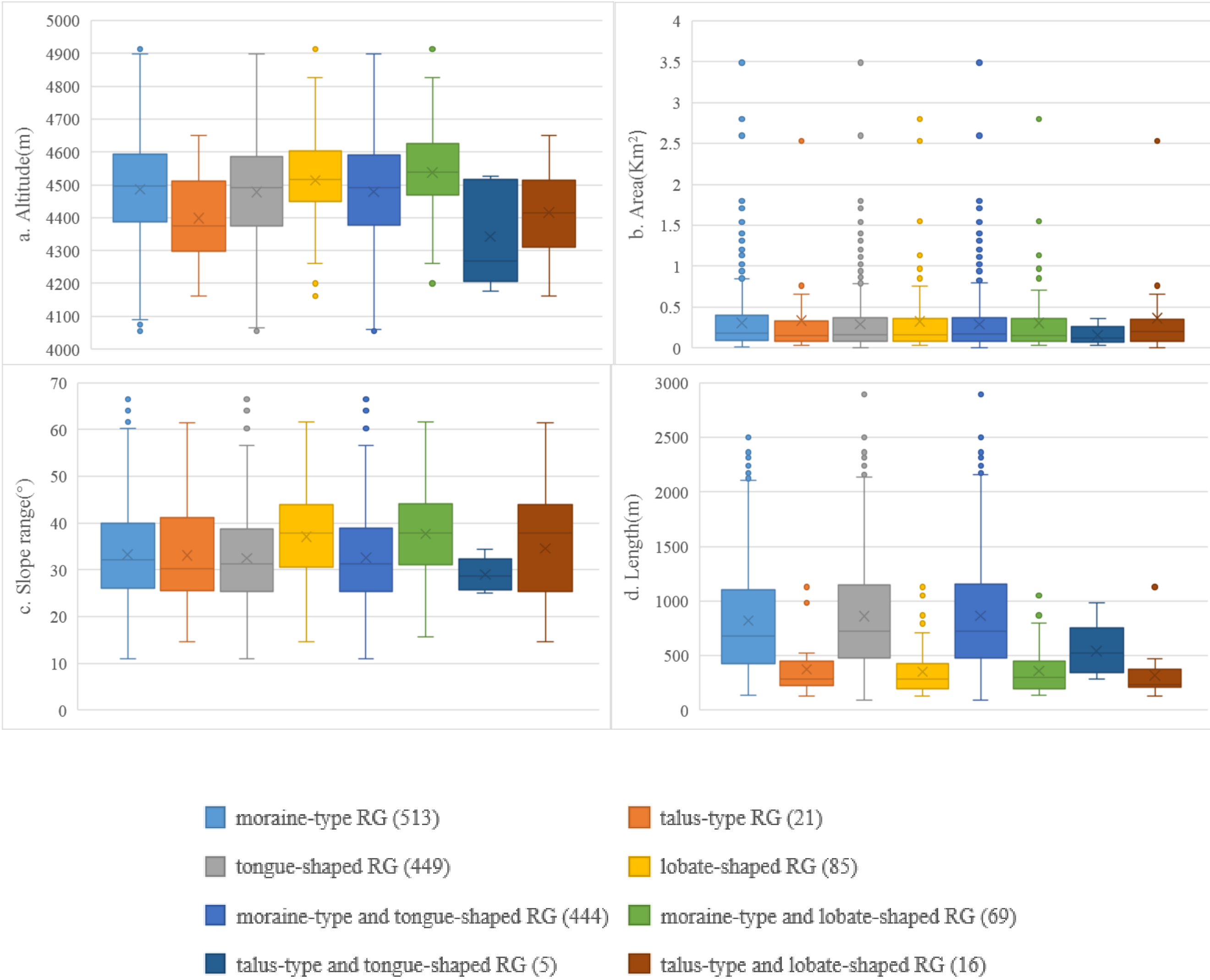

Figure 4: Boxplots illustrating the distributional characteristics of rock glaciers in the Daxue Shan: (a) altitude (m asl); (b) area (km^2); (c) range in the gradient of the slope (°); and (d) length (m). Boxplots represent 25-75% of all values, the caps at the ends of the vertical lines represent 10-90% of values, and the line in the center of each box indicates the median value. The number of the population of the different kinds of rock glacier is in the brackets of the legend.

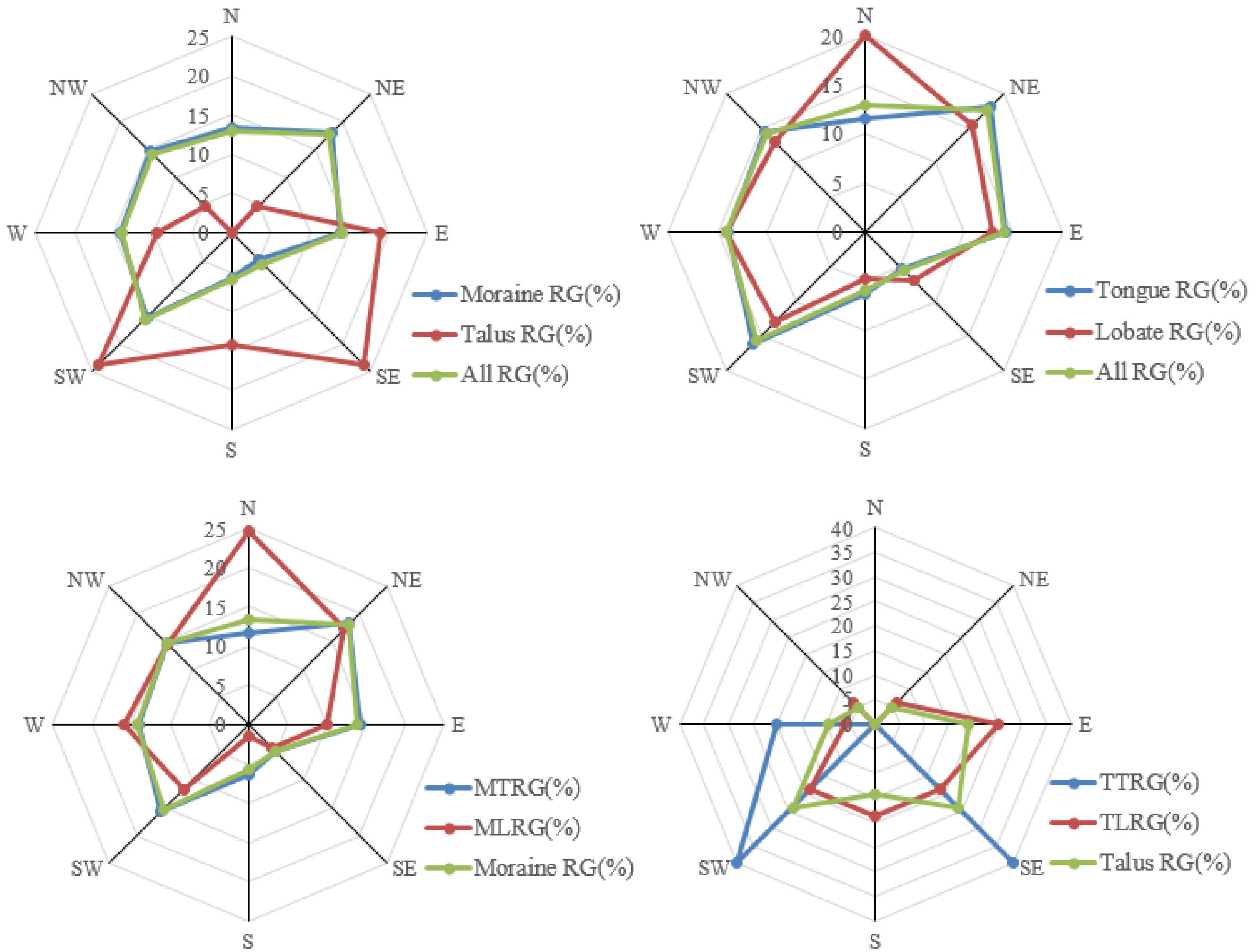

Figure 5: Analysis of the abundances of different rock glacier types versus aspect. The number of rock glaciers for each aspect on each of the four radar plots is shown as a percentage (%).

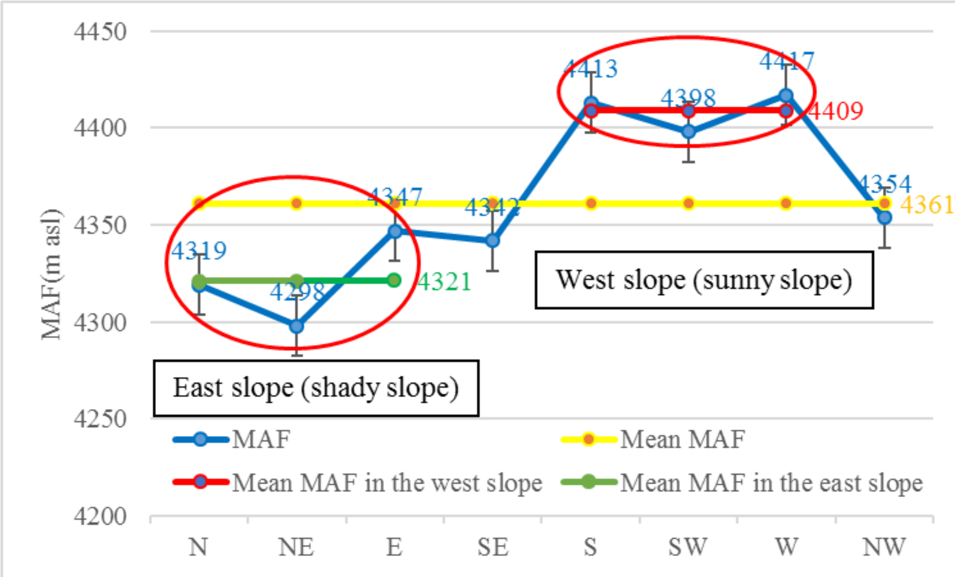

Figure 6: Minimum altitudinal rock glacier fronts (MAF) for all eight aspects, along with the overall mean. These values are taken to represent the lower boundaries of the potential permafrost extent in the Daxueshan region (bars indicate standard errors of the mean). Because the Daxue Shan lie along an approximately NW-SE axis, we used this NW-SE axis as the boundary separating east-facing (*i.e.*, N, NE, E), shady slopes from west-facing (*i.e.*, S, SW, W), sunny slopes.

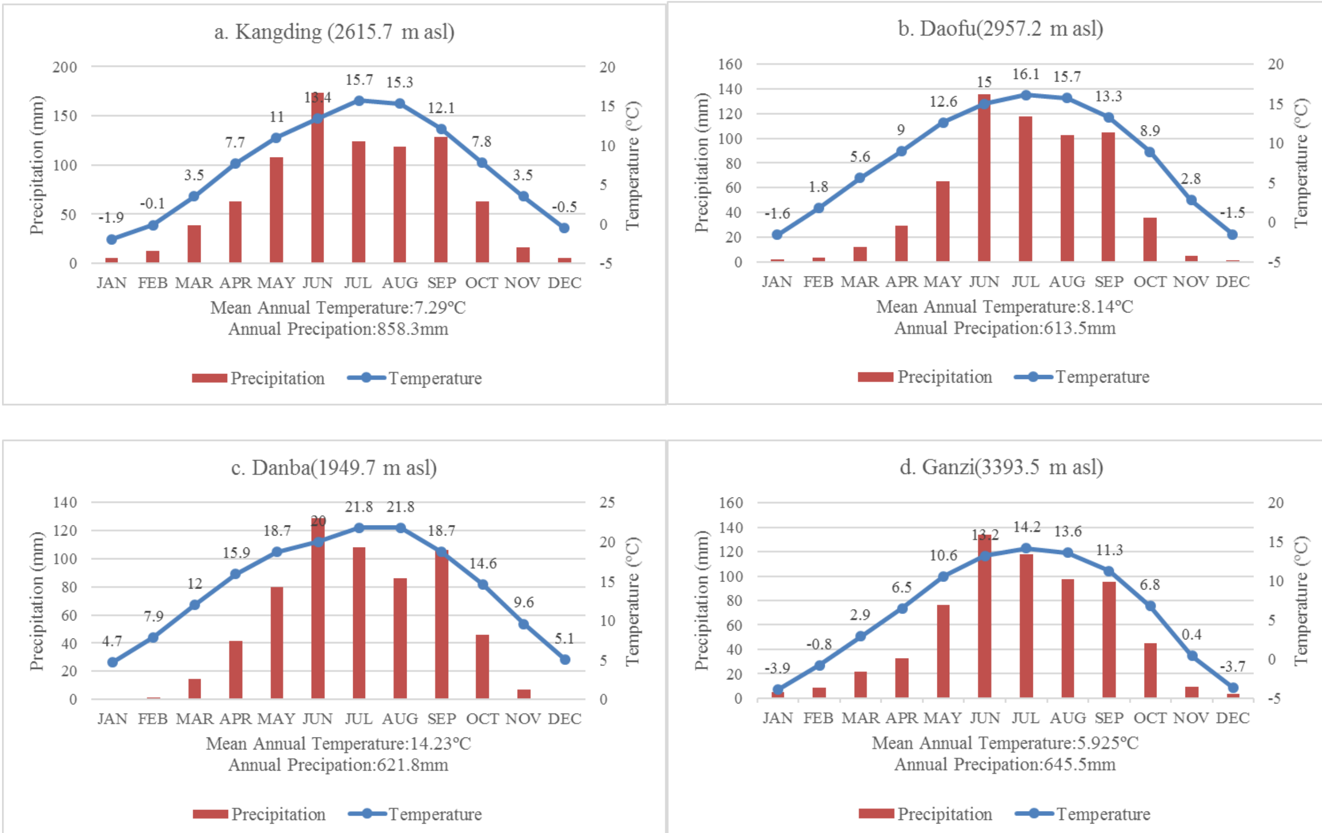

Figure 7: Climatographs for the Kangding (2,615.7 m asl, 30.03°N, 101.58°E), Daofu (2,957.2 m asl, 30.59°N, 101.07°E), Danba (1,949.7 m asl, 30.53°N, 101.53°E) and Ganzi (3,393.5 m asl, 31.37°N, 100°E) meteorological stations. Data sources: Meteorological Data Center of the China Meteorological Administration (calculated for the period 1981–2010, inclusive).

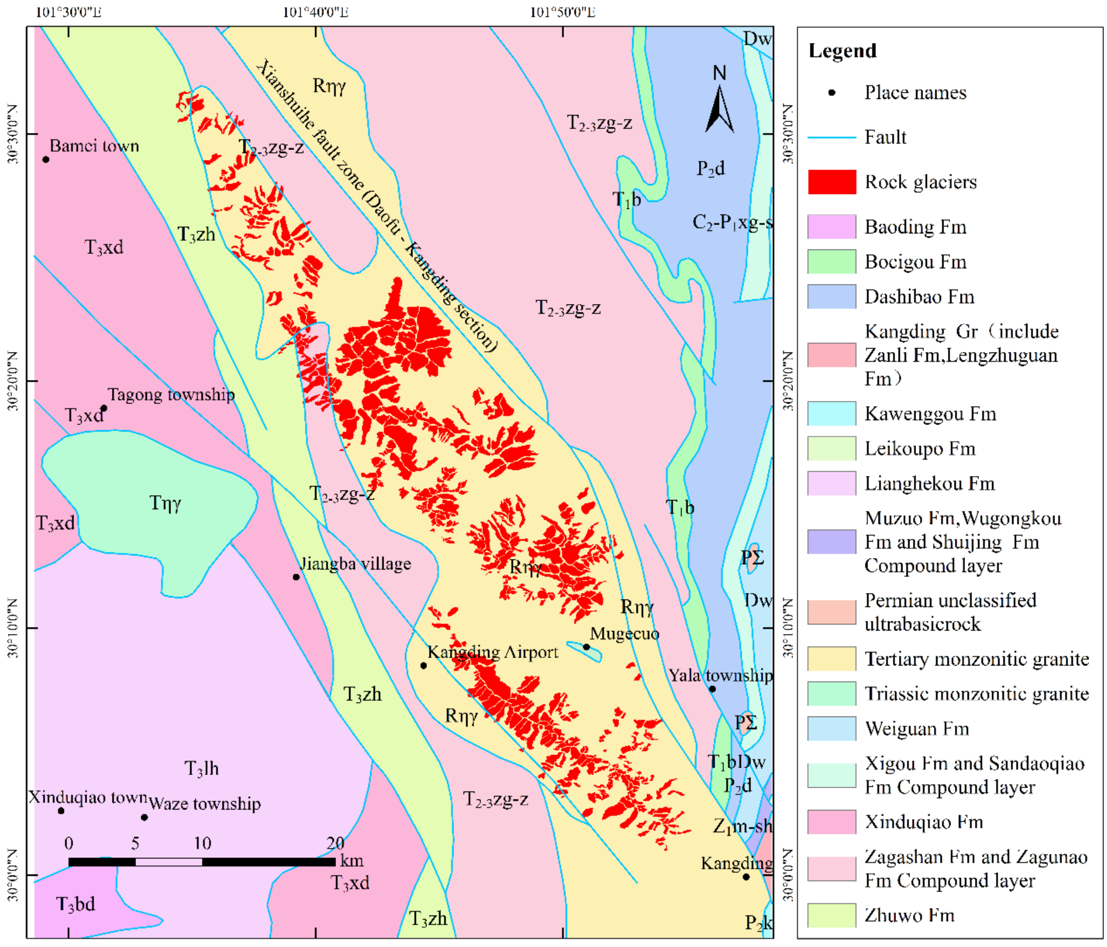

Figure 8: The rock glaciers of the Daxue Shan rock glaciers superimposed on the local lithologic-geologic environment (lithological map reconstructed from a 1:500,000-scale digital geological map).