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

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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

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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 either tongue-shaped as they move downvalley, or move outward from the valley sides in a lobate shape, they can be 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. 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 block-type 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 accurate 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; Triglav-Čekada et al., 2016; Janke et al., 2017; Wang et al., 2017), 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), estimations of the distribution of permafrost beneath rock glaciers (*e.g.*, Allen et al., 2008; Boeckli et al., 2012; Schmid et al., 2015; Sattler et al., 2016), and the dynamic movement of rock glaciers (*e.g.*, Haeberli et al., 2006; Liu et al., 2013; 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). Any study of the rock glaciers of the Daxue Shan on the southeastern margins of the TP has therefore been minimal. 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 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. Based on these criteria, 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) 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:

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

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, 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, 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. 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. 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 and development 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.

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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 (Table 3). 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 (Table 3). 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, meaning that the climatic environment would provide temperature and precipitation conditions highly favorable to the formation and development of 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 7 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 7 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)

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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.

4.3 Ideas for future research

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. 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. In addition, 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. 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.

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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

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Table 3. Climatographs for the Kangding, Daofu, Danba and Ganzi meteorological stations. Data sources: Meteorological Data Center of the China Meteorological Administration (calculated for the period 1981–2010, inclusive).

Meteorological station	Latitude	Longitude	Altitude (m asl)	Mean annual temperature (°C)	Mean annual precipitation (mm)
Kangding	30.03°N	101.58°E	2,615.7	7.29	858.3
Daofu	30.59°N	101.07°E	2,957.2	8.14	613.5
Danba	30.53°N	101.53°E	1,949.7	14.23	621.8
Ganzi	31.37°N	100°E	3,393.5	5.925	645.5

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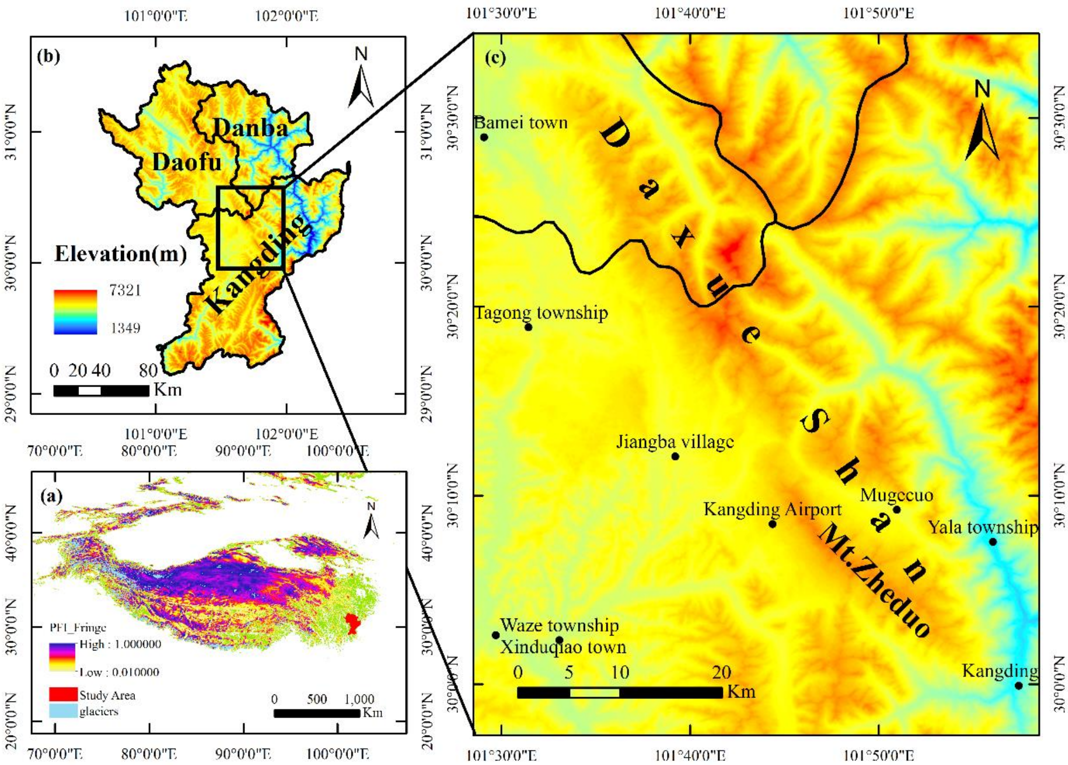

Figure 1: (a) The location of the study area in the permafrost zone of the TP. The Permafrost Zonation Index (PZI), or a corresponding map color, indicates to what degree permafrost exists only under the most favorable conditions (yellow), or nearly everywhere (blue); the map was produced using a temporal 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.

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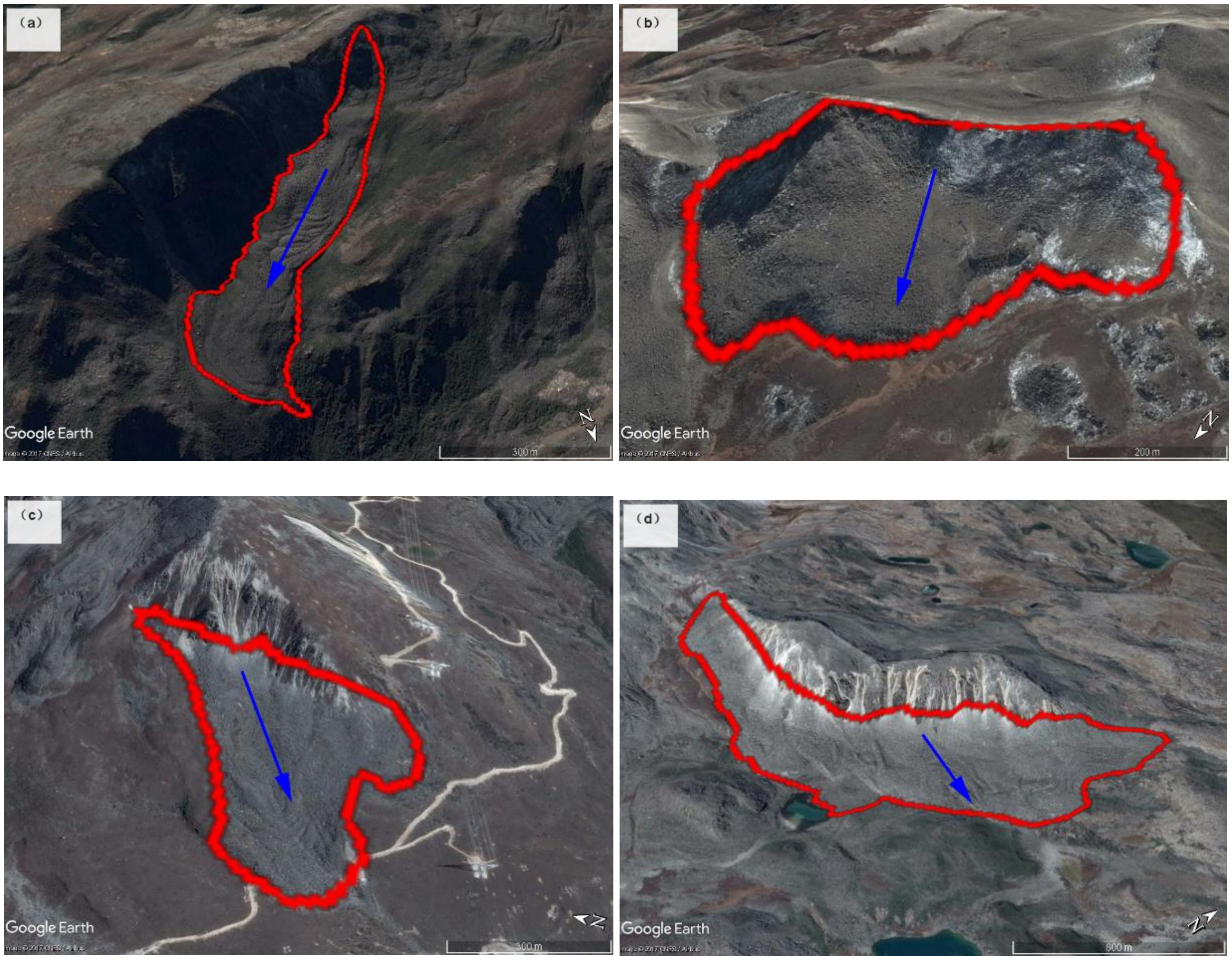

Figure 2: Examples of different types of rock glaciers in the Daxue Shan: (a) moraine-type and tongue-shaped rock glaciers (30.040597ºN, 101.911783ºE) (23rd November, 2015); (b) moraine-type and lobate rock glaciers (30.217147ºN,101.791585ºE) (15th November, 2015); (c) talus-derived and tongue-shaped 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.

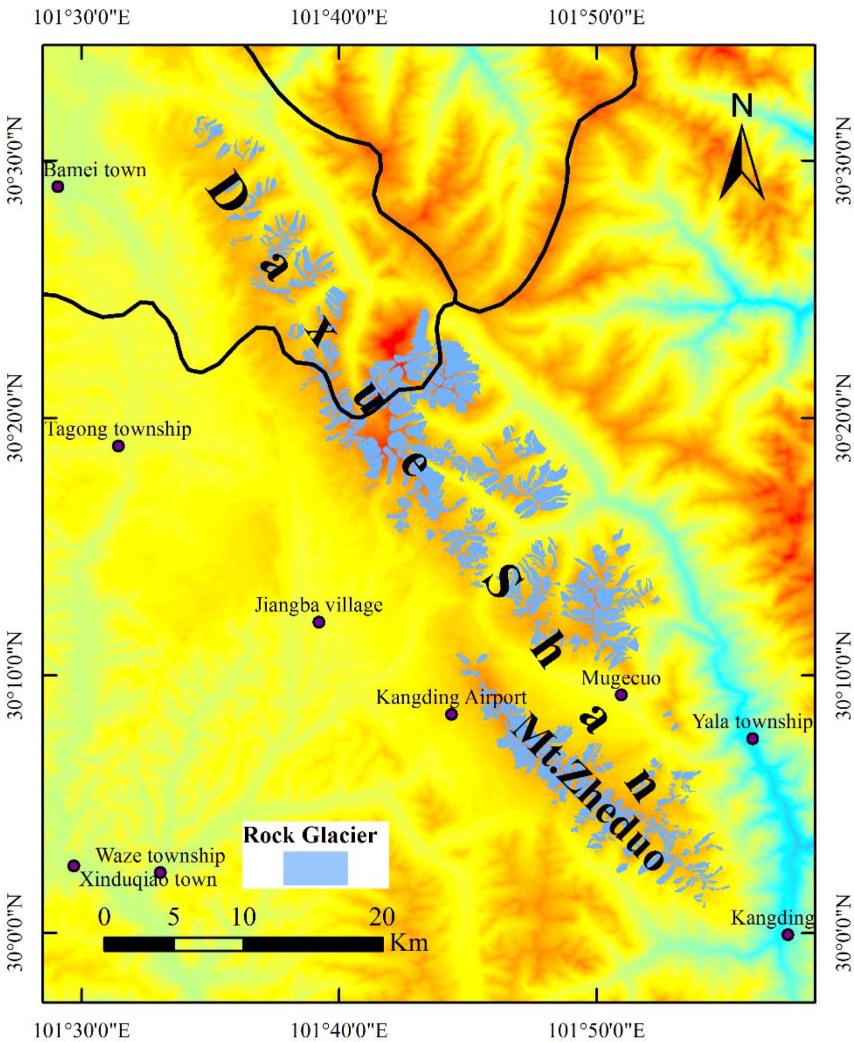

Figure 3: Spatial distribution of rock glaciers in the Daxue Shan.

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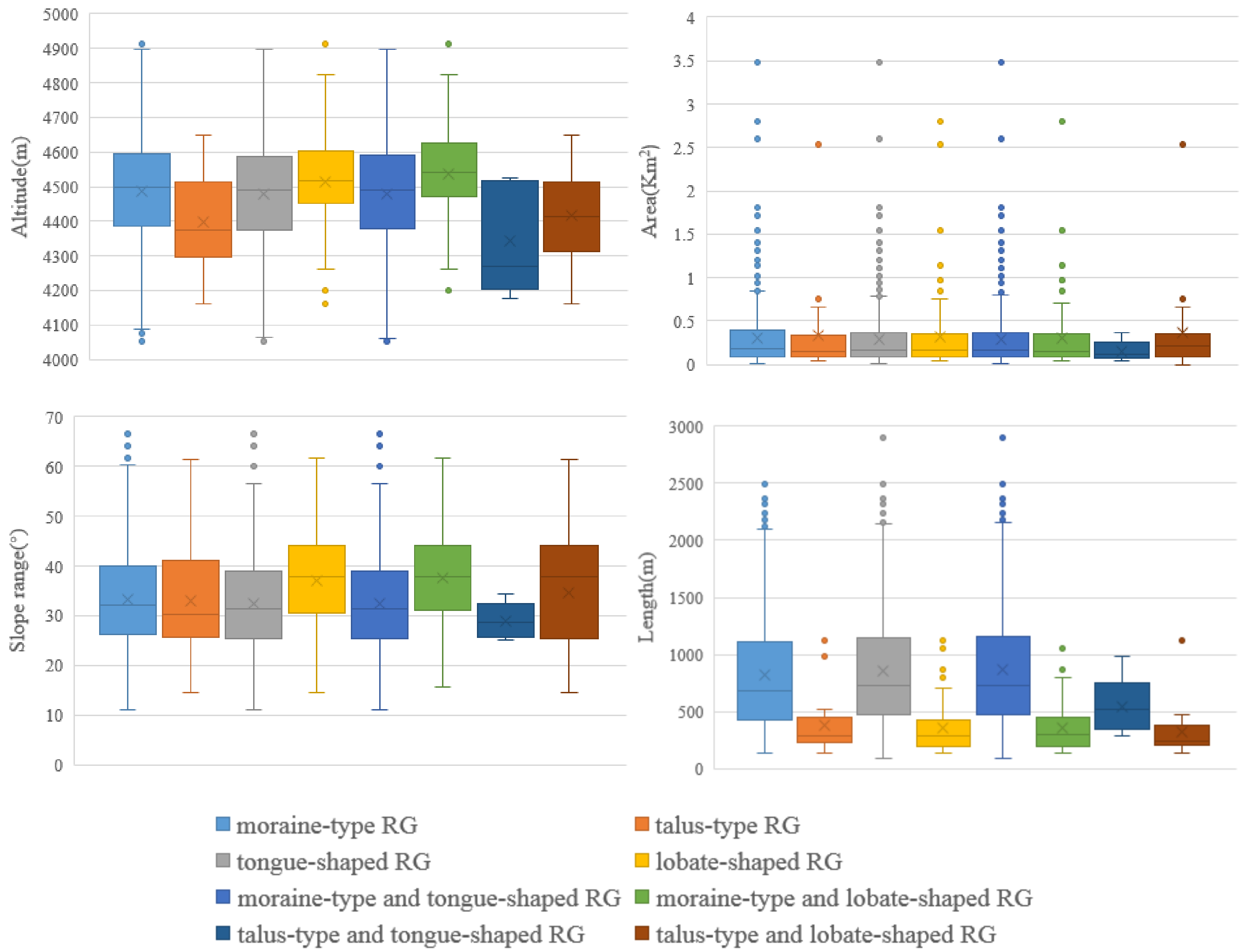

Figure 4: Boxplots illustrating the distributional characteristics of rock glaciers in the Daxue Shan: (a) altitude (m asl); (b) area (km^2); (c) range in the gradient of the slope (°); and (d) length (m). Boxplots represent 25-75% of all values, the caps at the ends of the vertical lines represent 10-90%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

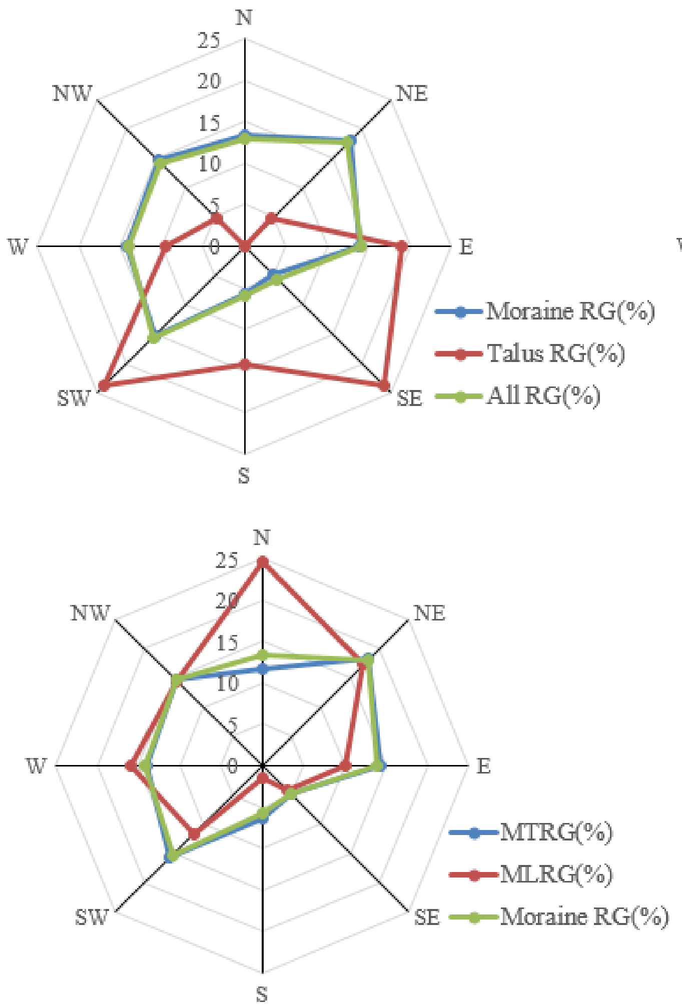

Figure 5: Analysis of the abundances of different rock glacier types versus aspect. The number of rock glaciers for each aspect on each of the four radar plots is shown as a percentage (%).

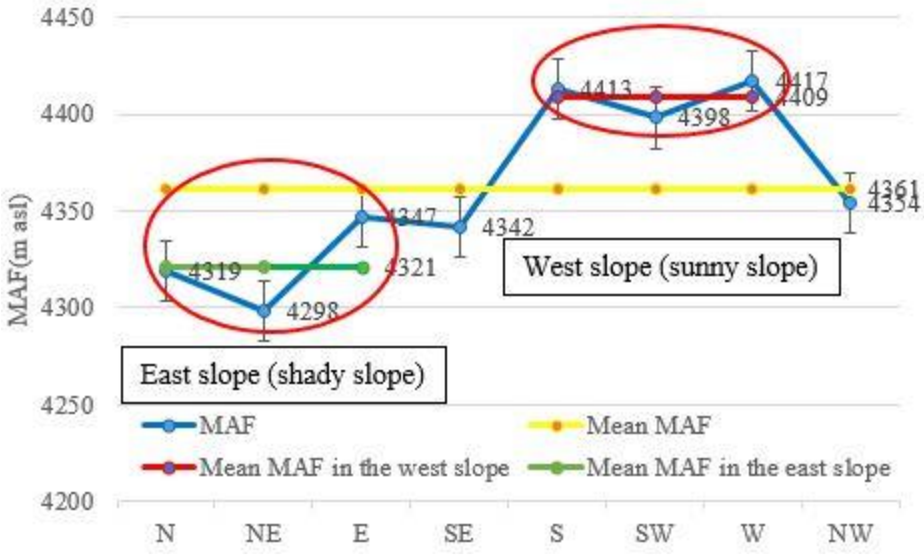

Figure 6: Minimum altitudinal rock glacier fronts (MAF) for all eight aspects, along with the overall mean. These values are taken to represent the lower boundaries of the potential permafrost extent in the Daxueshan region (bars indicate standard errors of the mean). Because the Daxue Shan lie along 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.

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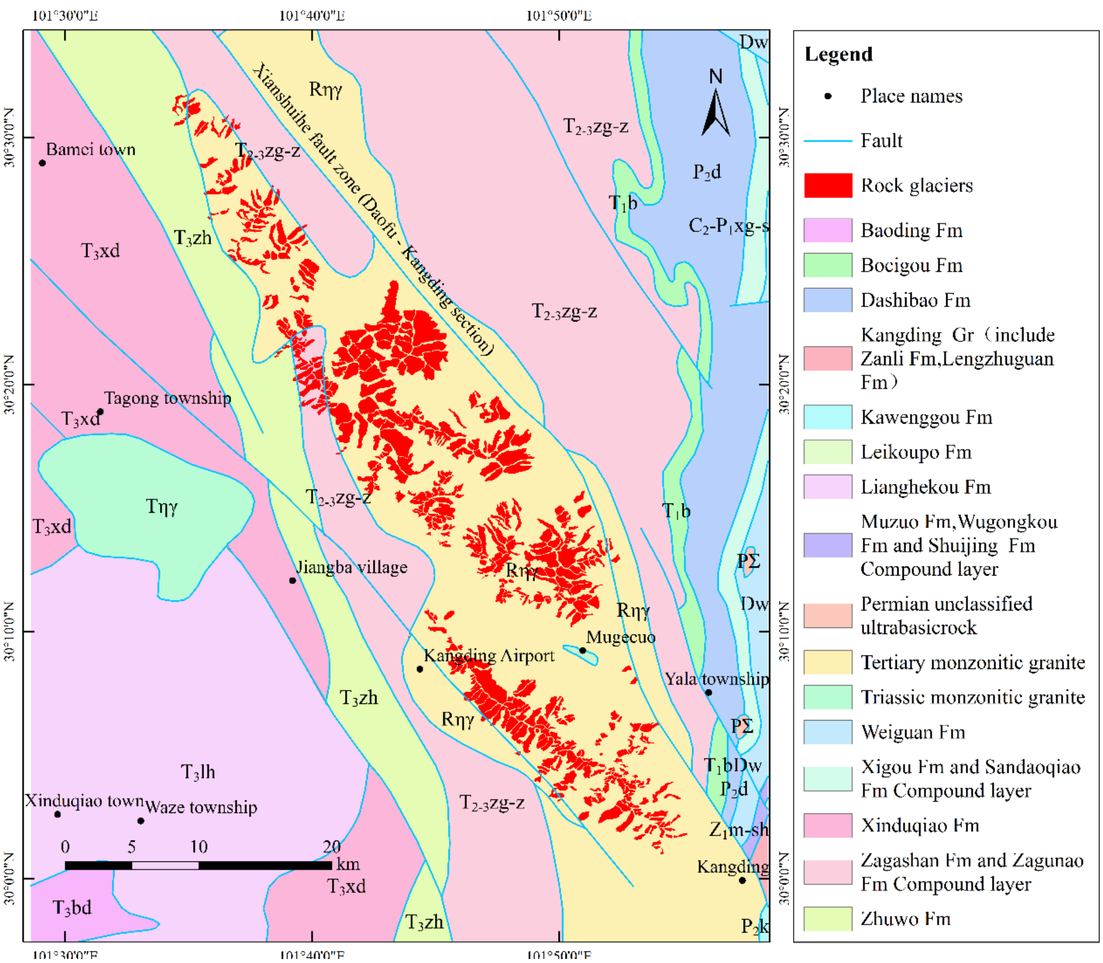

Figure 7: The rock glaciers of the Daxue Shan rock glaciers superimposed on the local lithologic-geologic environment (lithological map reconstructed from a 1:500,000-scale digital geological map).