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Application of frequency ratio and logistic regression to active rock glacier occurrence in the Andes of San Juan, Argentina

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ABSTRACT

This study employs statistical modeling techniques and geomorphological mapping to analyze the distribution of active rock glaciers in relation to altitude, aspect, slope, lithology and solar radiation using optical remote sensing techniques with GIS. The study area includes a portion of the Dry Andes of the Cordillera Frontal of San Juan around 30°S latitude, where few geomorphological studies have been conducted. Over 155 rock glaciers have been identified, and 85 are considered active. The relationship between the variables and the rock glaciers distribution was analyzed using the frequency ratio method and logistic regression models. The analytical results show that elevations >3824 m a.s.l., a south-facing or east-facing aspect, areas with relatively low solar radiation, and slope between 2° and 20° favor the existence of the rock glaciers, and demonstrate that lithology and slope exert major influences.

1. Introduction

Rock glaciers frequently occur in dry, continental mountain areas. Barsch (1996) characterized them as geomorphological expressions of creeping mountain permafrost (Fujii and Higuchi, 1978), and they serve as indicators of past and present mountain permafrost (Haeberli et al., 2006). Therefore, rock glaciers provide valuable information on past atmospheric and hydrological conditions in relation to climate change, and key components of the debris-transport system especially in dry and continental high mountain areas such as the Central Andes (Brenning, 2005). The presence of permafrost, in an actively moving rock glacier, indicates a relatively cold climate; therefore inactive or fossil rock glaciers point to past colder climates. Additionally, the role of these periglacial features is of critical importance in arid mountain ranges because snow packs and glaciers act as long-term reservoirs for water, releasing a steady flow over the course of a year.

Based on their morphology, rock glaciers are classified into tongue-shaped rock glaciers (Wahrhaftig and Cox, 1959; White, 1971; André, 1992) when their length is greater than their width (Martin and Whalley, 1987; Hamilton and Whalley, 1995), and lobate or talus rock glaciers, when their length is shorter than their width (Wahrhaftig and Cox, 1959). Outcalt and Benedict (1965) categorized them by topographic position within the valley, calling them valley-floor (equivalent to tongue-shaped rock glaciers) or valley-wall rock glaciers (equivalent to talus-shaped rock glaciers). These classification systems seem to work well when rock glaciers are identified using remote sensing techniques based on their general appearance.

Various authors have studied rock glacier distribution (Chueca, 1992; Johnson et al., 2007) to determine factors controlling rock glacier development. Inventories of rock glaciers have been collected to investigate the influence of lithology (Evin, 1987), topography (Wahrhaftig and Cox, 1959; White, 1979; Ellis and Calkin, 1983), and climate (Thompson, 1962; Ellis and Calkin, 1979; Harris, 1981; Brazier et al., 1998; Brenning, 2005; Brenning and Trombotto, 2006; Brenning et al., 2007) on their development.

The aim of this study is to discuss the distribution of active rock glaciers in the Andes of San Juan, Argentina, in relation to altitude, aspect, slope, lithology and solar radiation, by analyzing topographical maps and satellite images, and using the frequency ratio and logistic regression models.

2. Regional setting

The study area is located in the middle west of Argentina and the northwest of San Juan Province, Iglesia Department, between latitudes 29°41′–30°5′S and longitudes 69°23′–69°39′W, on the northeast side of the Cordillera Frontal, characterized by high relief with peaks up to 5000 m a.s.l (Fig. 1). The study area is characterized by semi-arid conditions with dry climates, short-lived summers and rigorous winters with very low temperatures (−18 °C to 0 °C), scarce precipitation and strong winds. According to Köppen (1936), the climate in the study area corresponds to the E type (Cold Climates) where permanent ice and tundra are always present. The temperature is always below 10 °C. From 3300 to 4300 m a.s.l., the climate is the Et

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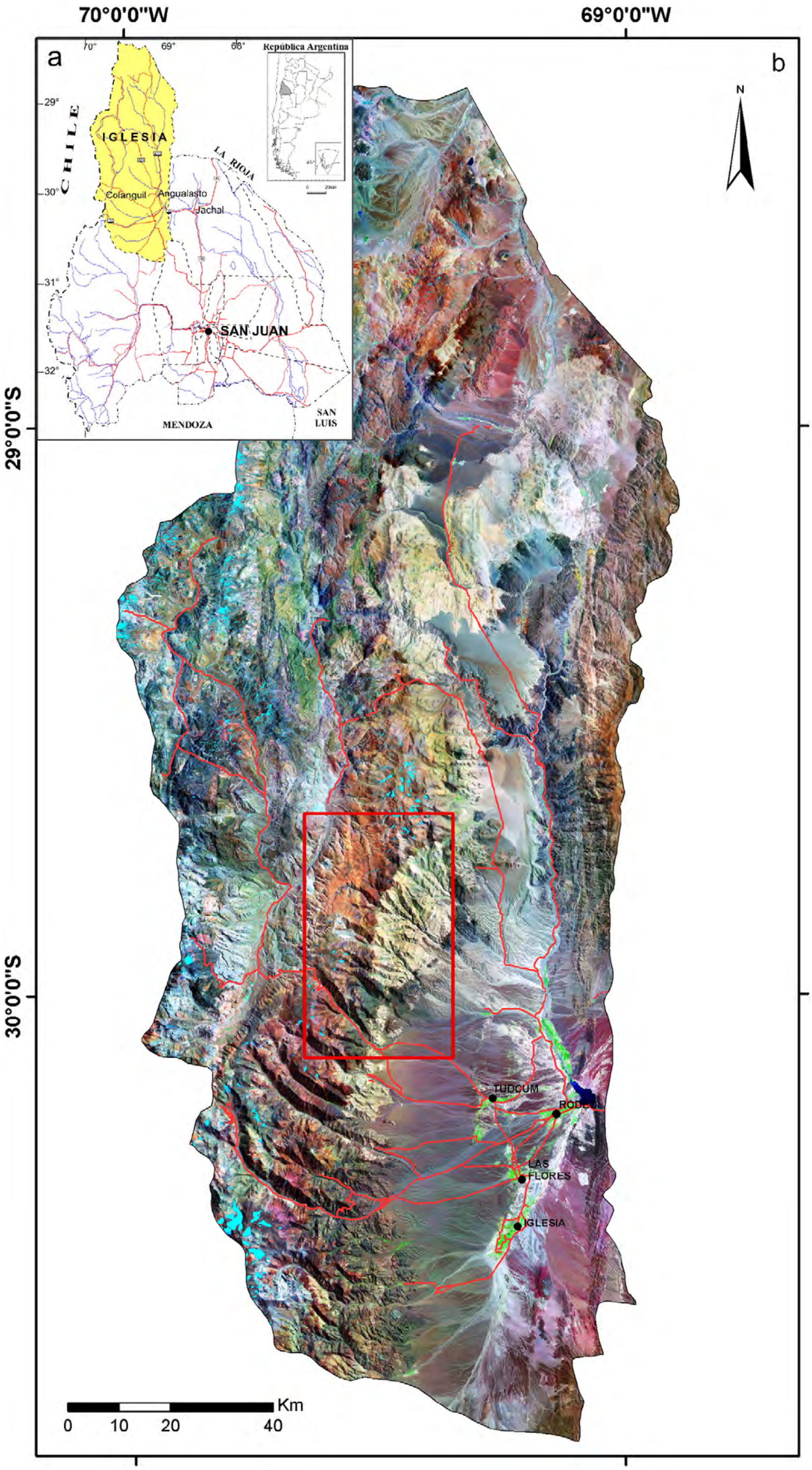

Fig. 1. Geographic location of the study area. (a) San Juan Province, Argentina. (b) Iglesia Department. The rectangle represents the specific study area.

type, high mountain tundra, with temperatures between −18 °C to 10 °C and the dry and high mountain Eb type, characterized by summer precipitations. Above 4300 m a.s.l., the climate type is Ef with perpetual ice, where the average temperature in January is below 0 °C and favors the formation of permafrost. Above 4000 m a.s.l. the precipitations are mainly snow and frost; precipitation events are infrequent and of irregular frequency. Annual precipitation for most of the area is between 100 and 200 mm (Minetti et al., 1986).

The Cordillera Frontal geological province is mainly made up of a suite of Upper Paleozoic rocks which unconformably overlie a Middle Proterozoic substratum (Ramos, 1999) and highly deformed Lower Paleozoic sedimentary rocks. The oldest stratigraphic unit in the area is a sedimentary unit mainly composed of Upper Carboniferous–Lower Permian dark green mudstones interbedded with sandstones and conglomerates. This unit is overlain unconformably by a Permian–Lower Triassic mesosilicic and silicic volcanic and igneous complex including pyroclastic, subvolcanic and intrusive rocks, which consists of a lower andesite to dacite section and an upper rhyolitic section. Both units are intruded by medium-grained Triassic greyish granodiorites, which in turn are intruded by pink-red rhyolitic bodies. The sequence continues with an Eocene unit composed of conglomerates, sandstones, multicolor tuff, andesites, breccia and ignimbrite which rests unconformably on the Permo-Lower Triassic volcanic complex and is intruded by Miocene intrusive rocks of varied composition (granodioritic, andesitic, dacitic, dioritic, and granitic). The Paleogene–Neogene is represented by sedimentary units, composed of alluvial and colluvial deposits. The modern deposits, gravels, sands, marls, and clay, occupy the valleys and river beds.

3. Materials and methods

An inventory of rock glaciers in the study area was prepared (Esper Angillieri, 2008), in order to identify their possible relationships with environmental factors such as altitude, slope, aspect, lithology and solar radiation. The rock glaciers were identified using SPOT digital satellite images with a 2.5-m spatial resolution, taken in April 2008, which were georeferenced within a geographical information system (GIS).

The subdivision of rock glaciers into active, inactive and fossil was based on morphological criteria (Wahrhaftig and Cox, 1959; Martin and Whalley, 1987). In general we can say that active rock glaciers have a steep (>35°) frontal slope and a well-developed flow-like morphology defined by sets of parallel, curved ridges separated by long V-shaped furrows, while inactive rock glaciers show a gentler frontal slope and small deep meltwater lakes which can only be explained by the melting of ice below the debris layer. On the other hand, relict or fossil rock glaciers have rounded and subdued topography, and several meters of subsidence have occurred in them due to permafrost melting.

Altitudes were obtained from 1:100 000 topographic sheets with a 50-m contour interval published by the Instituto Geográfico Militar (Argentine Military Geographic Institute), and from topographical information obtained from the Radar Shuttle Topographical Mission (USGS, 2000). Then a digital elevation model (DEM) with a 15-m grid spacing was interpolated (Fig. 2). Using the DEM, slope aspect (Fig. 3), slope angle (Fig. 4) and the amount of solar radiation (Fig. 5) were calculated. Solar radiation (in WH m^{-2}; equal to 0.001 h of sun), in January and February was estimated using the hemispherical viewshed algorithm developed by Rich et al. (1994), Fu and Rich (2000, 2002) and Rich and Fu (2000). Geologic sheets published by the Servicio Geológico Minero Argentino (Argentine Mining Geologic Service) on 1:250 000 scale were used to determine the rock type (Fig. 6).

Using the frequency ratio method and a logistic regression model (Lee and Sambath, 2006; Lee and Pradhan, 2007), relationships between the presence of active rock glaciers and environmental variables were analyzed. The frequency ratio is the ratio of the probability of an occurrence to the probability of a non-occurrence for given attributes (Bonham Carter, 1994). Therefore, the frequency ratio (F_r) can be calculated according to the following equation:

$$F_r = \frac{N_i}{N} / \frac{S_i}{S} \quad (1)$$

where S is the total number of pixels, N is the number of pixels with rock glaciers occurrences, S_i is the number of pixels the i factor or variable, and N_i is the number of pixels in which the rock glaciers occurred in the i attribute or factor. If F_r is greater than 1, it means a higher correlation, and a value smaller than 1 means lower correlation. Logistic regression is useful for predicting the presence (1) or absence (0) of a phenomenon based on a set of predictive variables. The advantages of logistic regression are: 1) each variable used can be either continuous or discrete, and 2) it does not necessarily have a normal distribution. In the present situation, the binary dependent variable represents the presence or absence of a rock glacier. In a logistic regression analysis, it is preferable that the number of pixels representing areas with a phenomenon and that without it should be the same (e.g., Ayalew and Yamagishi, 2005). In the study area, 19548 pixels represent the active rock glaciers. Therefore, 19548 pixels without rock glaciers were randomly selected for logistic regression. The lithologic units and aspect classes were treated as categorical variables, and slope, elevation, and solar radiation as continuous variables. Because semantically distinct parameters may have a strong correlation, the Pearson correlation coefficient was used to check correlations between variables.

4. Results and discussion

A total of 85 active rock glaciers, occupying an area of 4.40 km^2, were identified. The majority of them (61) are talus rock glaciers; only 24 are tongue-shaped ones. However, the latter occupy a greater area (2.85 km^2) than the former (1.55 km^2).

The Pearson correlations (Table 1) show that the variables used in the present study are only weakly correlated with each other. The highest correlation was found between solar radiation and slope (−0.588).

The observed distribution of the active rock glaciers, the frequency ratio and logistic regression coefficients are shown in Table 2. The factors chosen and the system constructed were found to be valid; with 81.8% of the pixels used being correctly predicted (83.8% of the pixels of the active rock glaciers and 79.9% of non-rock glaciers). Furthermore, the logistic regression analysis revealed that the distribution of the active rock glaciers can be explained mainly by slope and lithology, because if these two factors were considered, 79.9% of the pixels were correctly classified.

As the slope angle increases, the frequency of the active rock glaciers decreases. For slopes <15°, the frequency ratio is >3, but for slopes >25°, the ratio is <1.

The active rock glaciers commonly occur in valleys dominated by piroclastic, subvolcanic and intrusive rocks of the Permo-Triassic volcanic complex (78.88%). Although the areas underlain by the Miocene, Eocene and Permian units have altitude, slope, aspect and solar radiation similar to those of the rest of the valleys, the rock glaciers in the areas are relatively rare because the areas occupy only 0.72%, 4.42% and 3.94%, respectively, of the study area, whereas the Permo-Triassic volcanic complex occupies 49.43%.

All the active rock glaciers mapped occur above 3824 m a.s.l., pointing to the possible minimum elevation for the development of rock glaciers. More than 92% of them develop between 4000 and 5000 m a.s.l., but a frequency ratio of 1.293 and a coefficient of logistic regression of 0.001 mean a weak effect of altitude.

Although most active rock glaciers occur on east-facing (45°–135°) and south-facing (135°–225°) slopes, frequency ratios of 1.524 and

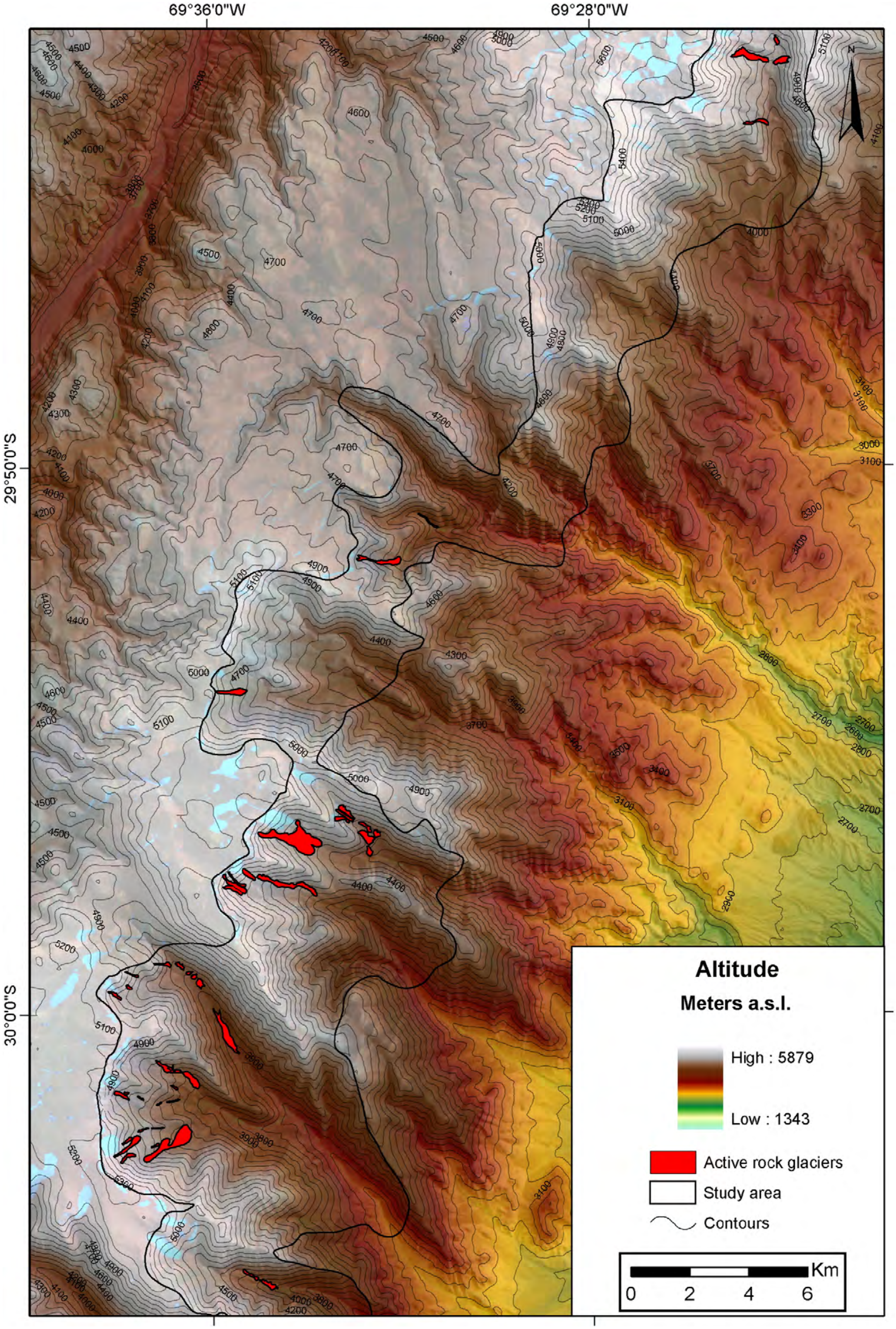

Fig. 2. Map of altitude and active rock glaciers.

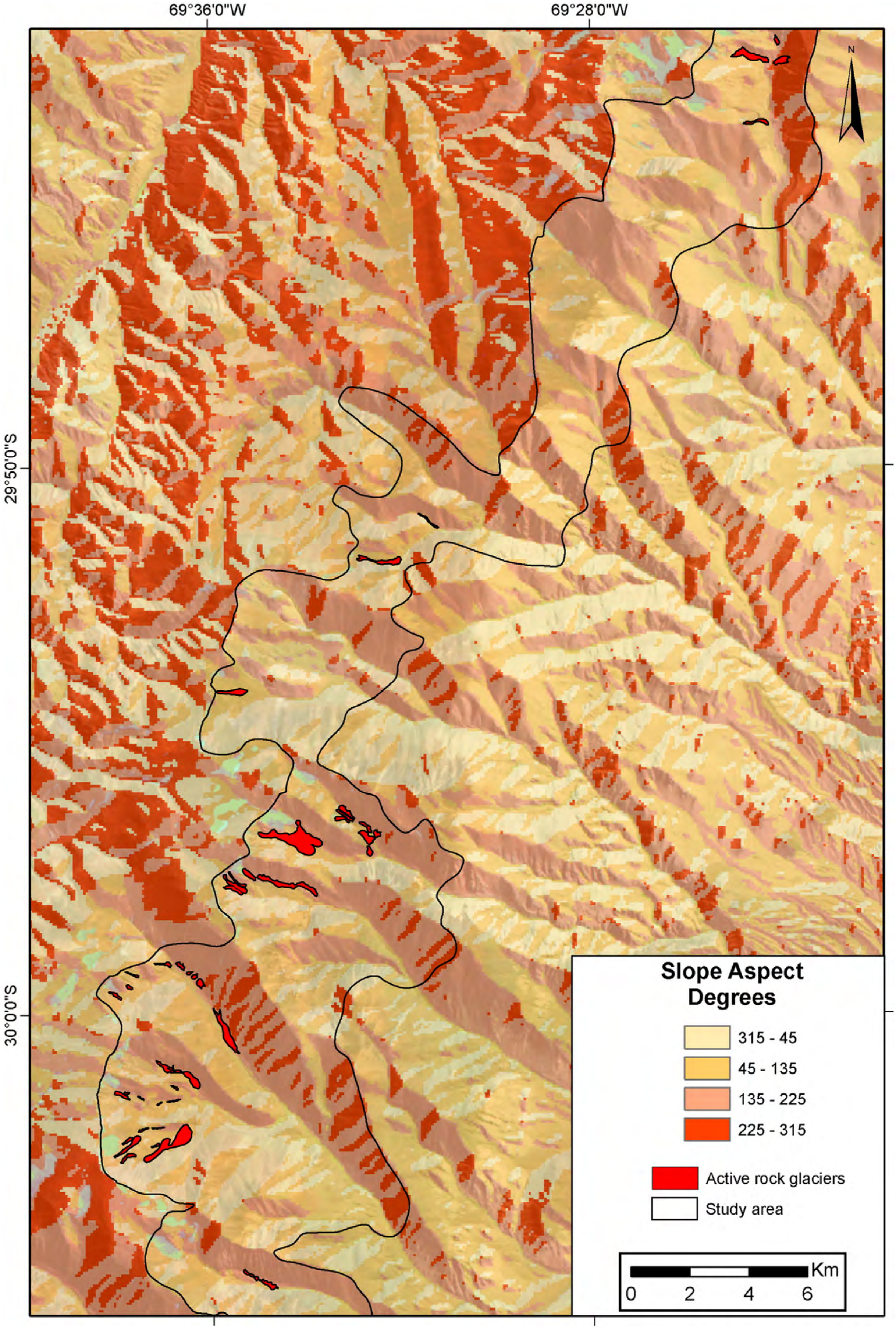

Fig. 3. Map of slope aspect and active rock glaciers.

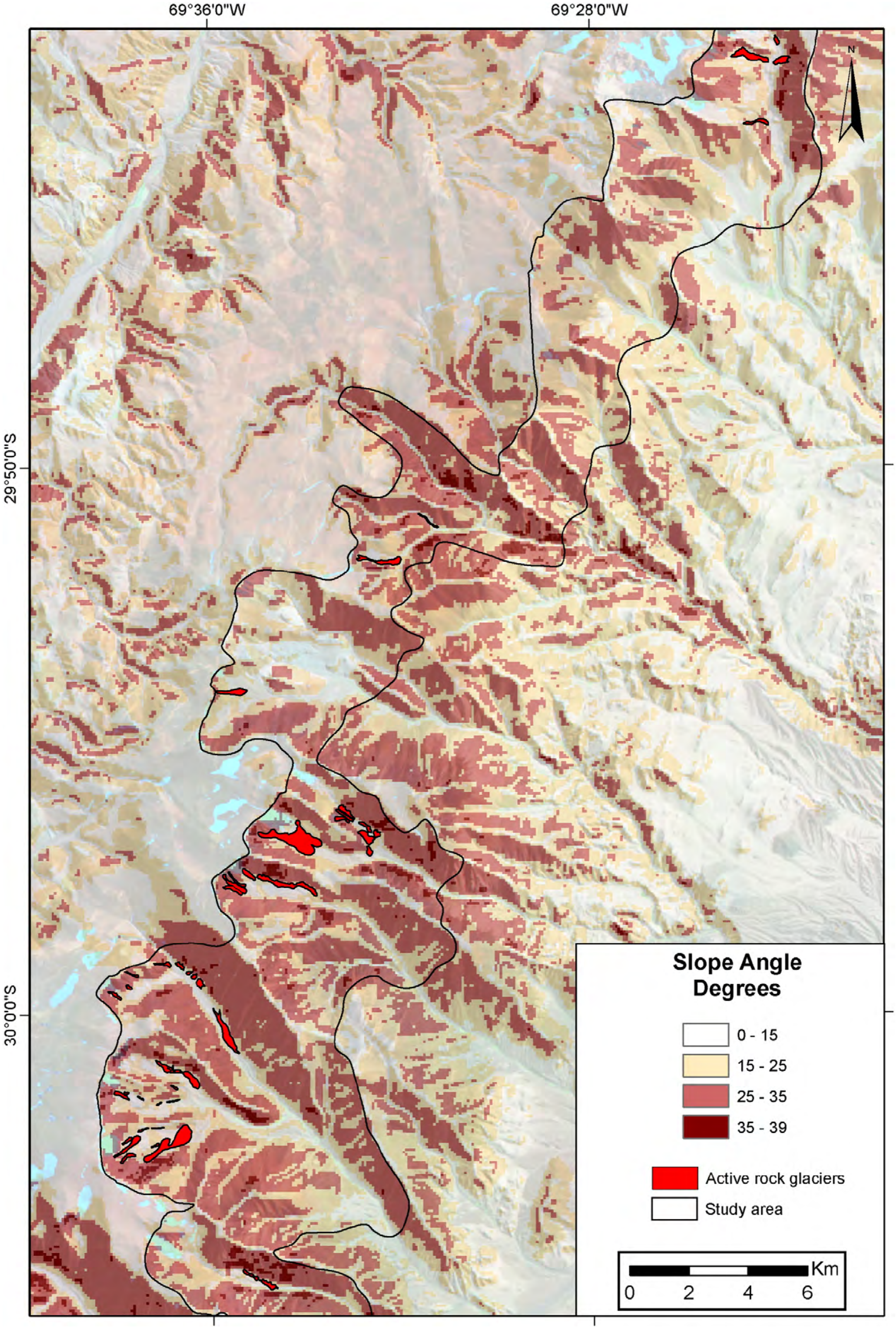

Fig. 4. Map of slope angle and active rock glaciers.

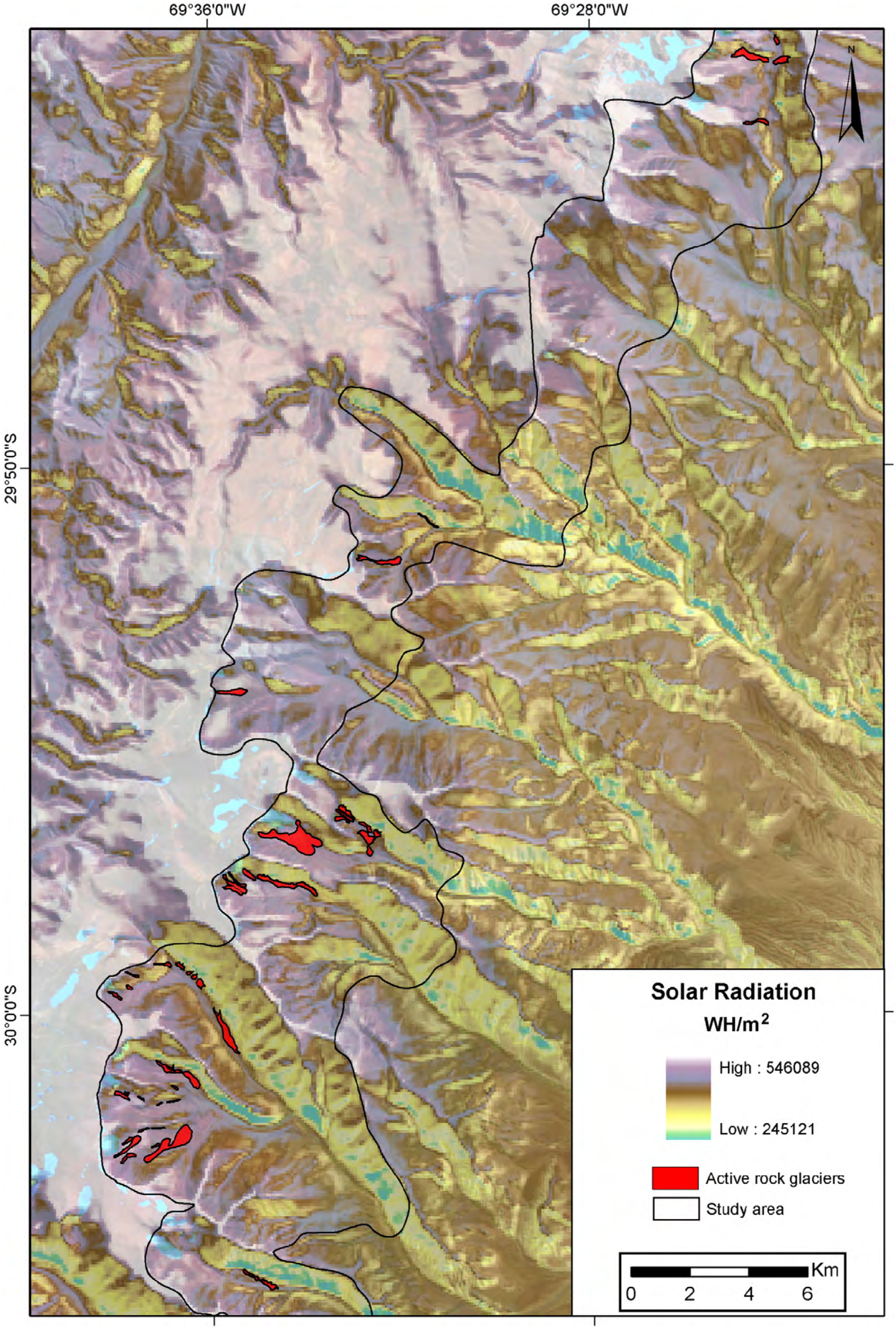

Fig. 5. Map of solar radiation and active rock glaciers.

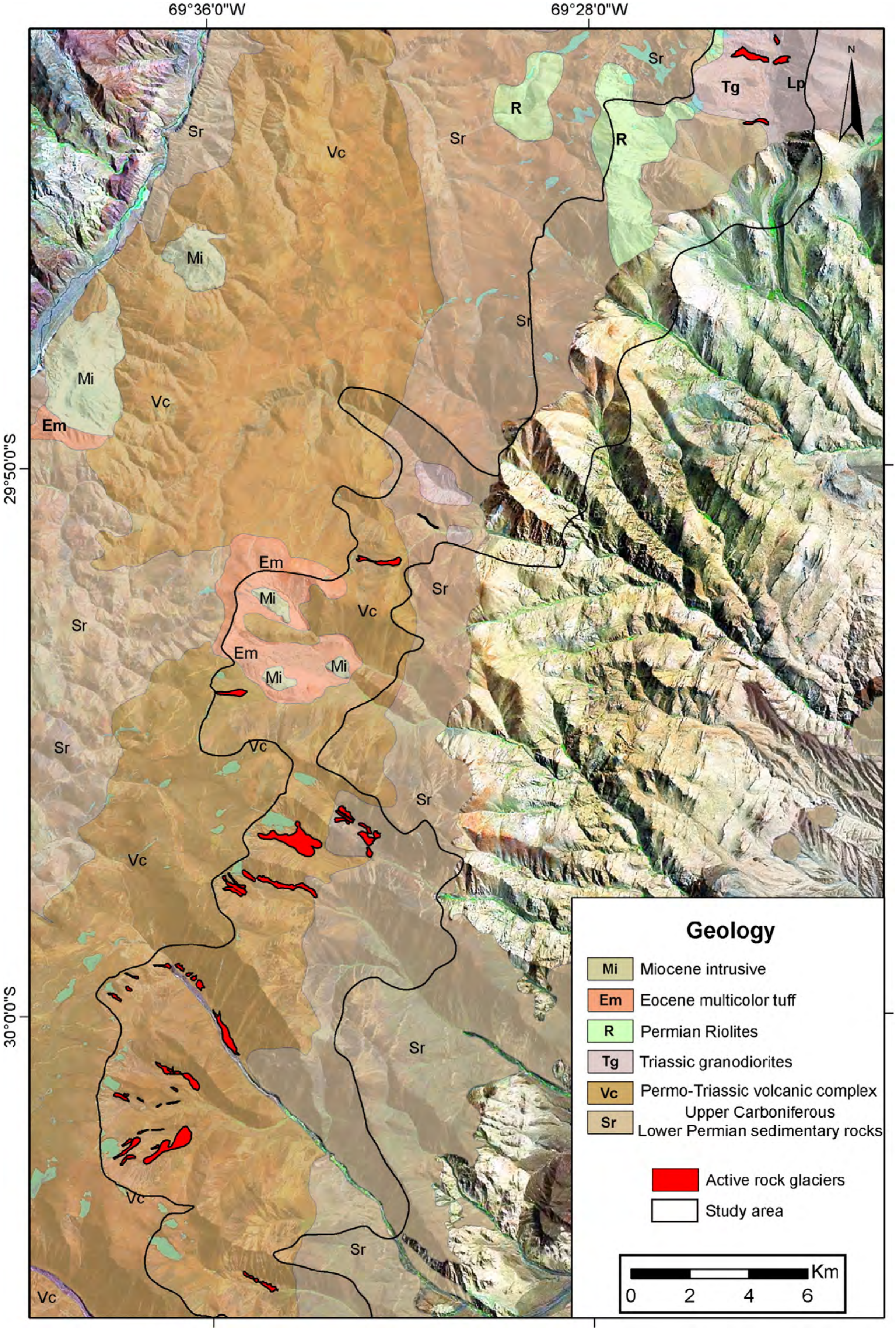

Fig. 6. Map of geology and active rock glaciers.

Table 1
Pearson's correlation coefficients between variables.

	Elevation	Aspect	Slope	Lithology	Solar radiation
Elevation	1.000	−0.061	0.040	−0.062	0.538
Aspect	−0.061	1.000	0.035	0.068	−0.416
Slope	0.040	0.035	1.000	−0.201	−0.588
Lithology	−0.062	0.068	−0.201	1.000	0.087
Solar radiation	0.538	−0.416	−0.588	0.087	1.000

0.985 and coefficients of logistic regression of 0.226 and 1.387, respectively, mean a weak influence of aspect. However, if we consider aspect with topographic positions, >79% of the active rock glaciers located along valley walls occur on south-facing slopes, and >77% of those located along valley floors occur on east-facing slopes. These observations indicate a greater influence of aspect in areas with relatively low sun insolation.

The active rock glaciers in the study area receive solar radiation amounts between 3.66×10^5 and 4.90×10^5 WH m^{-2} corresponding to 366 to 490 h (low solar radiation), but low frequency ratio values and a coefficient of logistic regression of −0.024 mean a weak effect of solar radiation. In contrast, the San Juan Province receives an average solar radiation of 13 h per day during January and February, which is equivalent to a total of 835 h (high solar radiation).

5. Conclusions

The logistic regression analysis revealed that the distribution of the active rock glaciers in the Dry Andes of the Cordillera Frontal of San Juan can be explained mainly by two factors: slope and lithology, with some additional influences of elevation and aspect. All active rock glaciers lie above 3824 m a.s.l., pointing to the possible minimum elevation for rock glacier formation. A gentle slope angle below 15° is also favorable. Another influence of aspect can be inferred if topographic position is considered. South-facing and east-facing slopes are a condition for their occurrence on valley walls and bottoms. However, solar radiation is not considered as a significant variable.

Nevertheless, similar conditions of altitude, slope, and aspect do not always result in similar development of rock glaciers, reflecting control by lithology. The active rock glaciers form preferentially in valleys dominated by the Permo-Triassic volcanic complex. Lithology affects the amount of debris production and water storage in debris, resulting in varied rock glacier distributions according to lithology.

The results obtained in this study have provided an advanced knowledge of the distribution of rock glaciers in the Andes of San Juan. Furthermore, the methodology presented here is easy to reproduce and may be applied to other mountainous regions, as a useful tool to assess periglacial environments in relation to geologic and topographic settings.

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Table 2
Frequency ratios and logistic regression coefficients for different variables.

Factor	Class	Number of pixels with rock glaciers[a]	% of pixels with rock glaciers[b]	Number of pixels in domain[c]	% of pixels n domain[d]	Frequency ratio[e]	Coefficients of logistic regression
Elevation [m. asl]	3000–4000	1287	6.584	231834	18.876	0.349	0.001
	4000–5000	18109	92.639	879659	71.620	1.293	
	5000–5643	152	0.778	116734	9.504	0.082	
Aspect [degree]	315–45	1261	6.451	235235	19.152	0.337	1.313
	45–135	10560	54.021	435239	35.436	1.524	0.226
	135–225	7302	37.354	465701	37.917	0.985	1.387
	225–315	425	2.174	92052	7.495	0.290	1.134
Slope [degree]	0–15	10685	54.660	182649	14.871	3.676	−0.202
	15–25	6542	33.466	395435	32.196	1.039	
	25–35	2265	11.587	588458	47.911	0.242	
	35–49	56	0.286	61685	5.022	0.057	
Lithology	Miocene intrusive	0	0.000	7603	0.725	0.000	−21.152
	Eocene multicolor tuff	0	0.000	46375	4.424	0.000	−20.270
	Permian Rhyolites	0	0.000	41289	3.939	0.000	1.367
	Triassic granodiorites	1800	9.208	68237	6.510	1.414	1.524
	Volcanic complex	15421	78.888	518194	49.436	1.596	0.150
	Sedimentary rocks	2327	11.904	366522	34.966	0.340	−17.254
Solar radiation [WH/m^2]	315660,37–362686,62	0	0.000	15993	1.302	0.000	−0.024
	362686,62–421469,43	1375	7.034	335573	27.322	0.257	
	421469,43–480252,25	15431	78.939	761577	62.006	1.273	
	480252,25–534332,43	2742	14.027	115084	9.370	1.497	

Total number of pixels with rock glaciers = 19548.
Total number of pixels in domain = 1228227.
$b = (a/19548) * 100$.
$d = (c/1228227) * 100$.
$e = b/d$.

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