Spatial and climatic characterization of three glacial stages in the Upper Krnica Valley, SE European Alps

Kozamernik, Erika; Colucci, Renato R.; Stepišnik, Uroš; Forte, Emanuele; Žebre, Manja

Published in:
Quaternary International

DOI:
10.1016/j.quaint.2017.05.047

Publication date:
2018

Citation for published version (APA):
Kozamernik, E., Colucci, R. R., Stepišnik, U., Forte, E., & Žebre, M. (2018). Spatial and climatic characterization of three glacial stages in the Upper Krnica Valley, SE European Alps. *Quaternary International*, *470*(A), 67-81. https://doi.org/10.1016/j.quaint.2017.05.047

Spatial and climatic characterization of three glacial stages in the Upper Krnica Valley, SE European Alps

[1]Erika Kozamernik, [2]Renato R. Colucci, [1]Uroš Stepišnik, [3]Emanuele Forte, [4]Manja Žebre

[1] Department of Geography, Faculty of Arts, University of Ljubljana, Aškerčeva 2, 1000 Ljubljana, Slovenia; e-mail address: erika.kozamernik@gmail.com; uros.stepisnik@ff.uni-lj.si

[2] Department of Earth System Sciences and Environmental Technologies, ISMAR-CNR c/o Area Science Park Basovizza, Q2 building S.S.14 - km 163.5 I-34149 Trieste, Italy; e-mail address: r.colucci@ts.ismar.cnr.it

[3] Department of Mathematics and Geosciences, University of Trieste, Via Weiss 1, 34128 Trieste, Italy; e-mail address: eforte@units.it

[4] Geological Survey of Slovenia, Dimičeva 14, 1000 Ljubljana, Slovenia; e-mail address: manja.zebre@geo-zs.si

Corresponding author: Manja Žebre; e-mail address: manja.zebre@geo-zs.si

Abstract

The southeastern European Alps represent the spot where mean annual precipitation is at its highest in the entire Alpine chain. Accordingly, the glacial evolution here might have a different spatial and chronological pattern if compared with other alpine areas. This paper discusses geomorphological evidence of three glacial stages from the Krnica Valley in the Julian Alps of Slovenia, and is the first step towards a comprehensive palaeoglaciological studies in this alpine sector. Very well-preserved glacial landforms in the Upper Krnica Valley allowed the reconstruction of glacier surface topographies and corresponding equilibrium line altitudes (ELAs) by means of field-based geomorphological and sedimentological data and by using geospatial analysis. The uppermost frontal moraines belong to the Little Ice Age (LIA) and the corresponding ELA is estimated at 1973 m a.s.l. Other two stages with the ELA depressed by 50 m and 161 m compared to the LIA ELA, suggest early Holocene and Younger Dryas ages of the palaeoglaciers, respectively. This assumption ensues from absolute age datings and related ELA depressions observed elsewhere in the European Alps. The presence of buried ice under the debris in the Krnica cirque, imaged through geophysical investigations, point to peculiar microclimatic conditions able to preserve relict glacier ice. This is favoured by the recursive presence of snow on the ground caused by the extreme summer shading and the significant winter snow-recharge triggered by snowblow and avalanche feeding. The possible evolution of such relict ice under the ongoing climate warming is also discussed.

Keywords: European Alps; ice patch; ELA; GPR; Holocene; Younger Dryas;

1. Introduction

Southeastern Alps were at the edge of a large Alpine ice cap during the Last Glacial Maximum (LGM) (Ehlers and Gibbard, 2004); however, the maximum extent of glaciers in this part of the Alps is in general not systematically documented, neither the deglaciation nor later Holocene glacial advances. The Julian Alps is the southeasternmost part of the Alps, stretching between Italy and Slovenia. This alpine sector is especially known for its high amount of precipitation, one of the highest in the entire Alpine chain (Norbiato et al., 2007). Four major glaciers in the Julian Alps (Tagliamento, Soča, Sava Dolinka and Bohinj) (Bavec and Verbič, 2011; Monegato et al., 2007) were draining the Alpine ice cap during the LGM, but only the terminal part of the Tagliamento glacier is both well-defined and precisely dated using absolute age-dating methods (Monegato et al., 2007; Fontana et al., 2008). Two glacial advances took place in this piedmont area (Monegato et al., 2007), earlier between 26 and 24.6 ka cal BP and later between 23.5 and 22 ka cal. BP (recalibrated by Monegato et al., 2017). The deglaciation period is only documented by some geological and geomorphological evidence in the hinterland of the main valleys (e.g. Bavec et al., 2004; Colucci et al., 2014; Monegato, 2012; Tintor and Andrič, 2014), however no datings or glaciological modelling exist for this period. A correlation of glacier advances after the LGM decay with those elsewhere in the Alps is also problematic (Reitner, 2007; Reitner, 2012) and LGM and Lateglacial fluctuations are generally documented only for the northernmost side of the eastern Alps (e.g., Van Husen, 1997; Reitner, 2007). Nevertheless, few works conducted on peat bogs in the Dolomites point to a rapid and complete deglaciation of alpine valleys at the end of the Lateglacial (Poto et al., 2013). On the contrary with well-studied Younger Dryas moraines in the central and eastern Alps (Ivy-Ochs, 2015), the evidence for the Younger Dryas as well as the early Holocene glacial advances in the Julian Alps is in general missing. Rock glacier`s distribution in the southeastern Alps suggests the Younger Dryas age for the documented relict landforms, with the majority of them situated between 1708 and 1846 m a.s.l. ; this represents the lowest rock glacier's altitude for the Alps (Colucci et al., 2016). The glacial evolution during the late Holocene has been recently also reconstructed by reproducing the glacial topographic changes from the Little Ice Age (LIA) to the year 2012 (Colucci, 2016; Colucci and Žebre, 2016). The glacierized area had shrunk by about 84 % since then and today only isolated very small glaciers and ice patches, covering an area of less than 0.5 km^2 still survive.

The Krnica Valley in the Slovenian Julian Alps (Figure 1) preserves several glacial deposits likely belonging to different stadials, which makes it a key area for Lateglacial-to-Holocene studies. The Quaternary filling of the valley floor is very complex, containing glacial and fluvial deposits, remobilized or superimposed by mass movement processes. First surveys on glacial deposits reported the presence of till and documented a series of lateral moraines at the valley outlet (Melik, 1955). Those findings were later confirmed by a series of geological drillings in the area (Pavlovec, 1961). In the spirit of the Alpine Lateglacial morphostratigraphic division set by Penck and Brückner (1901/1909) and solely on the basis of geomorphological evidence Melik (1955) suggested Bühl stadial age for these moraines. Further reports additionally deal with glacial deposits in the upper valley sections, where four series of glacial deposits were identified. These were ascribed to Lateglacial advances (Gams, 1992; Kunaver, 1999). Lower sections of the valley contain largely modified glacial deposits while within the upper section some well-preserved lateral and terminal moraines develop (Kunaver, 1999). The uppermost two parallel ridges enclosing the glacial cirque and behind which a series of perennial snow patches are today present, were associated with the LIA maximum (Colucci, 2016). Although some researches on Quaternary deposits and landforms in Krnica have been completed by now, more in-depth geomorphological and sedimentological data, allowing assumptions on glacial evolution and further chronological analyses, are still missing.

In this paper, we focus on the upper 5 km of the Krnica Valley in the Julian Alps, following four main aims: (1) to present detailed geomorphological evidence for several glacial stages in the Krnica Valley (Julian Alps) by using fieldwork and LiDAR data; (2) to present evidence for a still existing layer of glacial ice embedded by a thick debris layer in the Krnica cirque by interpreting ground penetrating radar (GPR) data; (3) to reconstruct glacial dimensions and related equilibrium line altitudes on the basis of field evidence and GIS analysis, and (4) to provide the glacial evolution of the Krnica Valley from the Lateglacial up to present-day in the framework of the Alpine glacial chronology.

2. Regional settings

The Krnica Valley is an approximately 9 km long valley in the northern Julian Alps of Slovenia which opens up heading north towards the Sava Valley. The latter is oriented along the active strike-slip Sava Fault (Jamšek Rupnik et al., 2012), here running in WNW-ESE direction, and represents the northern boundary of the Julian Alps. The highest peaks in the catchment area are Razor (2601 m) to the SW, Škrlatica (2740 m) to the E and Prisojnik (2547 m) to the W. The valley floor develops between altitudes of 2000 m and 810 m a.s.l., at the Kranjska Gora town. Our research area is located between 940 m and 2000 m a.s.l. within the valley where the best preserved glacial landforms are present (Figure 1).

Figure 1: (a) European Alps and location of Slovenia. (b) The Krnica Valley study area in the NW corner of Slovenia. 1 - Triglav-Kredarica observatory, 2 – Kranjska Gora, 3 – Rateče.

The valley belongs to the Julian Alps Overthrust Nappe, which is mainly built of Upper Triassic carbonates (Jurkovšek, 1987b) and is orientated along a number of regional and local faults (Jurkovšek, 1987a). Upper section of the valley has an alignment towards northwest, while the middle and lower sections have northward direction.

The morphology of the valley is significantly affected by geological settings. The wider sections of the main valley as well as few side valleys are located along sub-vertical strike-slip faults, which dissect the area mostly in NW-SE, and NE-SWdirections (Jurkovšek, 1987; Celarc and Kolar-Jurkovšek, 2008; Celarc et al., 2013). The NW-SE-striking faults belong to the Dinaric Fault System, which accommodates majority of active tectonic deformation in the region (Moulin et al., 2016). Also lithological settings influence the morphology of the slopes. Western slopes of the upper valley section are quite uniform with high steep rocky walls. They are mainly built of massive upper Triassic dolostone and limestone. The rest of the valley slopes are built of various Middle and Upper Triassic beds, which are completely dissected by a number of gullies. The majority of the eastern slopes and smaller sections of the western slopes, above the middle section of the valley, are mostly of Middle Triassic grey sparitic bedded dolostone and dolomitized limestone. Small segments of eastern slopes also consist of bedded Upper Triassic Dachstein limestone (Celarc and Kolar-Jurkovšek, 2008). Western slopes of the lower section of the valley are made of Middle Triassic limestone and dolostone with sporadic intercalations of marlstones (Celarc et al., 20013; Jurkovšek, 1987a, 1987b). The valley floor is entirely covered by different Quaternary deposits (Jurkovšek, 1987a, 1987b), mainly of glacial and slope origin.

The area is affected by the typical mountain climate of Slovenia (Tošić et al., 2016). Spatial distribution of annual and seasonal precipitation is strongly influenced by the topography, while thermal inversions play an important role in lowering the winter temperatures. Mean annual precipitation (MAP) in this alpine sector is one of the highest of the entire Alpine chain (Norbiato et al., 2007) and locally exceeds 3300 mm water equivalent (w.e.) (Colucci and Guglielmin, 2015) in the highest peaks. The 1981–2010 MAAT at 2547m at Triglav-Kredarica observatory (4.5 km SE of the uppermost Krnica Valley) was -1.0°C, being February the coldest (-8.1°C) and July the warmest (6.9°C) months. MAP (1981-2010) is 2038 mm w.e. In the valley at Rateče, located 5 km NE and at the same altitude of Kranjska Gora, 1981-2010 MAAT was 6.6°C and MAP 1459 mm w.e. At Kredarica and

Rateče 237 and 152 days with temperature <0°C are recorded on average in a year, while snow covers the ground respectively for 260 and 117 days. Annual snow accumulation is abundant with an average of 10.67 m at the Kredarica observatory (ARSO, 2017).

3. Material and methods

3.1 Geomorphological mapping

For field mapping purposes, topographic maps in scale 1:5.000, 1:10.000 and 1:25.000 (GURS, 1993, 1992; "Državna topografska karta Republike Slovenije 1:25.000. 041, Kranjska Gora," 1998), as well as hillshade images derived from a 1x1 m size cells LiDAR data (ARSO LIDAR, 2016) were used. Field data were additionally processed in ArcGIS 10.3.1. by means of orthophotos and LiDAR derived parameters, such as DEM (digital elevation model), hillshade, slope steepness, curvature, contours. These helped to precisely map and better analyse all previously identified landforms in the field. The mapping in the uppermost part of the valley, where the ground was covered by a thick snow cover during the LiDAR survey (2014-2015), was greatly supported by field photos and orthopotos in order to reconstruct the real topographic surface and relevant landforms. The focus was on distinguishing different series of moraines. Orthophotos from different years (1998, 2006, 2011, 2015) (GURS, 1998-2015) allowed us extracting the permanent snow patch boundaries in different years in the Krnica cirque and reconstructing its evolution over the last 18 years (1998-2016).

3.2 Ground Penetrating Radar (GPR) method

The use of Ground Penetrating Radar (GPR) for glaciological applications is well established since about 40 years with different purposes and various scales (e.g. Daniels, 2004). The reason is that the physical properties of frozen materials make possible the propagation of electromagnetic (EM) waves, on which the GPR technique is based, with limited attenuation. Indeed, the conductivity of frozen materials is one or two order of magnitude lower than most of the other geological materials (e.g. Jol, 2009) allowing a penetration depth of several tens of metres, or even more in favourable conditions, such as the absence of free water and the use of low frequencies. In addition, GPR can produce results with higher resolution than any other geophysical method, highlighting centimetric to metric variations in the dielectric parameters of the subsurface (in turn related to changes in density and texture of frozen materials) directly depending by the applied frequency range, typically from 25 MHz to about 1 GHz (Jol, 2009). Therefore, the most important objectives of GPR surveys mainly aim at measuring snow/ice thickness, determining their density, and imaging the ice/sediment stratigraphy.

On the 24th June 2015 we performed GPR measurements on the snow patches in the uppermost part of the Krnica Valley by using a ProEx Malå Geoscience equipment connected to a 500 MHz shielded antenna pair. The GPR was triggered by an odometer, obtaining a constant trace interval equal to 0.1 m. The wheel of the odometer was folded by a special rough film in order to minimize its slipping on the frozen surface. The transmitting and receiving antennas were parallel to each other and transverse to the survey direction, in order to minimize possible off line reflections. Two crossing profiles (P1 and P2) have been acquired in NE-SW and NW-SE direction, respectively, both of them reaching the top of the frozen body (Figure 5). The total length of the two profiles is limited to about 300 m, also due to logistic limitations. The main objective of such geophysical survey was to evaluate the thickness of the frozen deposit highlighting its internal stratigraphy; such goals drove the choice of instrumentation and acquisition parameters: the 500 MHz antenna was expected to reach both the desired depth of penetration and vertical resolution.

The GPR profiles were processed by using a flow that includes drift removal (i.e. zero time correction), bandpass filtering, background removal, geometrical spreading correction, depth conversion, and static (topographic) correction. We estimated the EM velocity field with dedicated diffraction hyperbola analyses validating and integrating the results by applying the amplitude inversion technique originally proposed in Forte et al. (2014b). The migration was not applied because diffractions have been used to better highlight the presence and the characteristics of the internal debris.

3.3 Reconstruction of palaeoglacier surfaces and calculation of their ELAs

A semi-automatic GIS tool named GlaRe (Pellitero et al., 2016) was used to reconstruct the palaeoglacier surfaces for three glacial stages in the Krnica Valley, while the pertaining ELAs were calculated via automatic ELA GIS tool (Pellitero et al., 2015a). ArcGIS 10.3.1 was used for running the tools. Glacier reconstruction is based on the numerical approach of Benn and Hulton (2010), but it is constrained by the geomorphological evidence indicating the former glacier geometry, such as lateral and terminal moraines, and trimlines. This approach is based on two assumptions: (1) the reconstructed glacier was in equilibrium with the climate, and (2) the present-day topography is the same as the palaeoglacier basal topography (Pellitero et al., 2016). Despite significant post-glacial mass movement processes in the Krnica Valley, we have estimated that these do not largely influence the input data (i.e. the present-day topography) for the glacier reconstruction. Moreover, the three youngest moraine sequences that were taken into account in our study are all well-preserved and are thus reliable adopted morphometric parameters for palaeoglacier surface reconstruction. User-defined inputs for the glacier reconstruction are: (1) a 1 m resolution DTM derived from LiDAR data (ARSO LIDAR, 2016) with point density from 2 up to 10 per m^2, and the relative horizontal and vertical accuracies of 0.30 and 0.15 m, respectively, (2) frontal or lateral moraines, (3) flowlines, (4) approximate spatial limit for the glaciers, estimated by the hydrological catchment and moraines. Since the procedure of reconstructing glacier surface is well presented in the paper of Pellitero et al. (2016), further steps used in our study are only graphically presented (Figure 2), and not explained in detail. Once having the glacier surfaces reconstructed, another GIS tool (Pellitero et al., 2015b) was used for a quick calculation of ELAs. The only input needed is the reconstructed glacier surface (DEM of palaeoglacier) (Figure 2). The tool allows calculating ELAs using the most commonly used methods, such as Accumulation Area Ratio (AAR), Area-Altitude Balance Ratio (AABR), Area-Altitude (AA) and Kurowski or Median Glacier Elevation (MGE) methods. In our case, the AAR method – the most widely applied technique for ELA estimation (e.g. Benn and Ballantyne, 2005; Hughes et al., 2010; Porter, 2001, 1975), was used. It is based on the assumption that the ratio between the accumulation area and the ablation area is fixed if a glacier is in a steady-state condition. Different AAR ratios are suggested in the scientific literature, depending on the type and size of a glacier, latitude and altitude, and the presence of debris cover. We used the ratio of 0.67, which is known to be the most reliable for most Alpine glaciers according to empirical studies (Gross et al., 1977). However, the ELA for each reconstructed glacier was calculated also by using other ratios between 0.2 and 0.8 (0.05 interval). This was done for easier comparison with other studies, where values different from 0.67 were used.

Figure 2: Methodological steps in the palaeoglaciers reconstruction and calculation of ELAs using GlaRe and ELA tool. Modified after Pellitero et al. (2016). Light grey circles are user defined inputs, dark grey squares are specific tools, while white circles are outputs. Bold texts are some user-defined values and bold line circles are the final outputs.

4. Results

4.1 Geomorphological settings

The Krnica Valley is a typical alpine U-shaped valley with a morphologically well-developed cirque in the valley head (Figure 3). Almost vertical 350-m-high slopes encircle the cirque floor from three sides, while two ~35 m high parallel frontal moraines (1 in Figures 3 and 4a) at 1910 m a.s.l. enclose this amphitheatre towards north. Both moraines are free of vegetation and blocky, hosting boulders having long axis up to 3 m, with the majority of those located on the ridges having about 1 m in diameter. Up-valley from these moraines two indistinct ridges of clast-supported diamicton between 1915 and 1955 m a.s.l. are present. These are located below an active gully in the cirque wall and are clearly a result of avalanche and mass movement processes. These perennial snow patches have already been documented on the old maps from 1913 (Badjura, 1913) and stated in the report of Gams (1961). Their recursive presence has been recognized also on the basis of orthophoto images from different years (Figure 5), as well as direct observations during the falls 2015 and 2016. Their areal extent shows a decreasing pattern between 1998 and 2015 (a reduction of approximately 9000 m^2), although we have to take into account slightly different days in which the orthophotos have been taken in summertime (Table 1) and that from such scarce data it is not possible to infer any trend.

Figure 3: Geomorphological map of the Krnica Valley. Numbers indicate the three different generations of moraines.

Figure 4: Aerial photos of (a) two parallel frontal moraines enclosing the cirque and snow patches on the 28th of October 2016, (b) a blocky moraine approximately 300 m down valley, and (c) a pair of lateral moraines, covered by vegetation and dissected by gullies. Moraine ridges are marked with white dashed line. Moraines in (a) are related to a first phase, moraine in (b) to a second one and moraines in (c) to a third phase, as shown in Figure 7. Numbers indicate the three different generations of moraines which have been attributed to the three glacial stages.

Further down valley, at 1845 m a.s.l., another frontal moraine characterized by even larger boulders from the upper two parallel moraines is present (2 in Figures 3 and 4b). The diameter of the largest boulders is approximately 10 m, while the average size from 1 to 3 m. This moraine is surrounded by talus deposits and is free of vegetation. About 200 m NNW, a pair of ca. 30 m high and 560-670 m long lateral moraines appear on the valley floor (3 in Figures 3, 4b and 4c). They extend between 1730 and 1400 m a.s.l. The distance between both ridges is 240 m in their upper part and only 100 m in their lower part. Both moraines are reworked by mass movement processes in the outer sections, whereas they are dissected by a deep gully in their internal and outflow section. The best preserved sections (the crests and the inner slopes) are overgrown by vegetation. The largest boulders, although less common if compared with upper laying moraines, reach sizes up to 2 m in diameter. Deposits within the moraines are normally consolidated clast-supported diamictons with prevailing 2-20 cm sub-angular clasts.

The valley distinctly widens below the lateral moraines. Owing to active fluvio-torrential and mass movement processes only erosional remnants of older moraines are here still preserved. Between 1290 m and 1140 m a.s.l., a ca. 20 m high mounds of blocky deposits cover the valley floor. Angular boulders having up to 10 m in diameter are common over the entire surface of the mounds, but especially in the lower section. The surface is covered by vegetation. Regarding the morphology and sediment characteristics, these deposits are likely of supraglacial origin, associated with a debris-covered glacier. Because of a huge amount of very big, angular boulders, they may be related to a rockfall over a glacier. Mass movement processes in the Krnica Valley are nowadays very active and they were likely even more active during and immediately after glaciations, when periglacial and paraglacial processes were largely affecting steep, ice-free slopes.

Other two moraine ridges situated below the Krnica Mountain hut, between 1090 m and 990 m a.s.l., were identified in the central part of the valley floor. These moraines are the least blocky in the entire study are, although up to 2 m large boulders can be found on their surface. They are completely overgrown by vegetation.

The lowest glacial deposits in the study area are essentially erosional remnants, partially covered by the alluvial fan, deposited from the left (W) side of the valley, and incised by a ca. 12-m-deep streambed. The size of the largest boulders is similar to the ones south of the Krnica Mountain hut. This moraine is also entirely covered by vegetation.

Other landforms, associated with mass movement and fluvial processes, also take place in the Krnica geomorphological setting, which makes this area very complex from a sedimentological point of view. They are not the focus of this research; however, their relationship with glacial features is essential for the final palaeo-glaciological interpretation. Alluvial deposits fill middle and lower sections of the valley floor, while talus deposits predominantly cover the slopes and slope processes often rework the in-situ glacial deposits. An evidence of a rockfall taking place on the 17th of April 2007 can be observed W from the Krnica Mountain hut (marked with * in Figure 3), while older rockfall material is also present in the Valley.

Figure 5: Orthophoto images of the Krnica permanent snow patch from different years. The location of the GPR profiles P1 and P2 is marked with black arrowed lines in the bottom right figure.

Table 1: Areas of the permanent snow patch between 1998 and 2015, based on orthophotos.

Orthophoto (year)	**Area (m^2)**
1998	37340
2006	37549
2011	23749
2015	28523

4.2 GPR survey

GPR processed data have been interpreted considering both amplitude and phase behaviour. In Figure 6 we provide the synthesis of the obtained results. The inferred velocity field, with velocities ranging from 0.22 m ns^{-1} close to the surface down to values of about 0.19 m ns^{-1}, suggests the presence of firn down to a high diffractive layer (BF). With the hypothesis of negligible conductivity and related losses, from the velocity it is possible to derive the dielectric permittivity and by empirical relations to estimate the density of frozen materials. We applied the relation proposed by Looyenga (1965) obtaining a density range between 450 and 680 kg m^{-3} (Forte et al., 2013). Such values are typical of *firn* (evidenced in transparent light blue on Figure 6) and exclude the presence of ice above BF. The maximum thickness of firn was estimated at 6.5 m both in the central and in the final (i.e. the uppermost) parts of profile P1, while it reaches more than 14 m in a small zone at the end of profile P2 and close to the cliff where the accumulation of snow of the avalanches is maximal. Within the firn, GPR data imaged several horizons (being H1 to H3 in Figure 6a the most evident) each of them marking a major density change and separating different snow falls or melting events. The diffractive zone (D) can be interpreted as the basal chaotic material laterally interconnected with the actual frontal moraine (M). The presence of a layer almost transparent from the EM point of view in the uppermost part of profile P1 between D and the interpreted bedrock (B) could lead to an alternative interpretation. Below the debris in the central and upper part of this feature a possible layer of thick relict ice (ICE? in Figure 6) might be present. This latter interpretation seems to be corroborated by the performed frequency attribute analyses (Zhao et al., 2016) which show a slightly different spectral content in the uppermost (ICE?) and lowermost (B) areas.

Figure 6: Synthesis of the GPR results. a) Interpreted GPR profile P1 without the topographic correction; b) Detail of a) better highlighting the bedrock (black arrows); c) 3D prospective view of profiles P1 and P2 plotted with a ratio between vertical and horizontal scale equal to 1. The light blue transparent zones highlight the firn; H1, H2 and H3 main horizons within the firn; M frontal moraine; B bedrock; D debris; BF base of firn; ICE? possible ice below the debris. See text for further details.

4.3 Palaeoglacier surfaces and palaeoELAs

Palaeoglaciers in all three stages in the Krnica Valley had northward orientation. The minimum altitude reached by the glacier in the Stage 1 was 1910 m, in the Stage 2 was 1845 m and in the Stage 3 was 1450 m a.s.l. The reconstructed palaeoglacier area for the first Stage is 0.058 km^2, for the second Stage 0.127 km^2 and for the third Stage 0.353 km^2 (Figure 7, Table 2). To verify if our reconstructions are consistent, we compared the reconstructed area and volume of the three stages in the Krnica Valley with the volume-area scaling power-law relationship (Equation 1) found in the Julian Alps by Colucci and Žebre (2016):

$$V=0.0328\ S^{1.1509} \qquad (1)$$

Results shown in Figure 8 with a linear trend on a log-log plot, only considering glaciers of the smallest size (i.e. <1.0 km2) as those taking place in the Krnica Valley during the Holocene, fit well with previous results based on different techniques or direct observations and geophysical surveys.

Figure 7: Map of three glacial stages and related ELAs.

Table 2: Some statistics concerning the reconstructed glacial stages in the Krnica Valley.

	Area (km^2)	Volume (km^3)	Max ice thickness (m)	Mean ice thickness (m)	Length (m)
Stage 1	0.058	0.001566	43	27	300
Stage 2	0.127	0.003937	55	31	600
Stage 3	0.353	0.018709	90	53	1600

Figure 8: Scatter plot of volumes vs. areas for all the glaciers in the Julian Alps (grey dots) during LIA and the three stages reconstructed for the Krnica Valley considering the smallest size glaciers having area < 1.0 km^2. Figure modified from Colucci and Žebre (2016).

The maximum ice thickness of the Stage 1 glacier was reconstructed to 43 m, the Stage 2 to 55 m and the Stage 3 to 90 m (Figure 9, Table 2). However, the ice thickness might be locally largely influenced by the deposition of younger (mainly glacial) deposits and postglacial slope reworking. The length of the first Stage glacier, without taking into account the highest 100 m in the cirque walls, was 300 m, the second Stage 600 m and the third Stage 1.6 km.

Figure 9: Map of ice thickness for the three reconstructed glacial stages.

The ELA was calculated for each glacial stage with the AAR method by using different ratios (Table 3). Since the ratio of 0.67 is suggested as the most reliable one for both cirque and valley glaciers in the Alps (Gross et al., 1977), all further comparisons within the studied valley as well as with other alpine glaciers are based on the ratio of 0.67. The ELA for the Stage 1 was calculated to 1973 m, for the Stage 2 to 1923 m and for the Stage 3 to 1812 m. The ELA depression associated with the Stage 3 with respect to the Stage 1 was calculated to 161 m. The ΔELA between the Stage 2 and Stage 3 was 50 m.

Table 3: ELAs for three reconstructed glacial stages using AAR method (with different ratios) and ELA depression versus youngest (Stage 1) reconstructed ELA.

Method	**Stage 1**	**Stage 2**	**Stage 3**	**ΔELA (Stage 1 vs. Stage 3)**	**ΔELA (Stage 1 vs. Stage 2)**
AAR 0.2	2243	2013	1992	251	230
AAR 0.25	2183	1998	1972	211	185
AAR 0.3	2023	1988	1952	71	35
AAR 0.35	2008	1978	1932	76	30
AAR 0.4	2003	1973	1917	86	30
AAR 0.45	1993	1968	1902	91	25
AAR 0.5	1988	1958	1877	111	30
AAR 0.55	1983	1948	1857	126	35
AAR 0.6	1978	1933	1837	141	45
AAR 0.65	1973	1928	1822	151	45
AAR 0.67	**1973**	**1923**	**1812**	**161**	**50**
AAR 0.7	1968	1918	1802	166	50
AAR 0.75	1963	1913	1772	191	50
AAR 0.8	1958	1903	1732	226	55

5. Discussion

Krnica Valley represents an interesting case study for the central-east sector of the alpine chain, mainly thanks to its very low anthropization allowing a very good preservation of at least three stages of glacial advance. Thanks to such evidence it has been possible to reconstruct three different palaeo-ELAs and link them to three climatic phases recognized in the Alps spanning from the Lateglacial to the late Holocene. The modern regional ELA in the Julian Alps is estimated at ca. 2700 m (Colucci, 2016) while the snow and firn patches permanently filling the Krnica cirque at present (in 2015) have a mean elevation of 1947 m and cover an area of 0.0285 km^2, which represents ca. 49% of the reconstructed Stage 1 glacial extent (Figure 7). The ELA for the latter has been estimated at 1973 m (AAR 0.67) (Table 3) and is very low if compared with other estimated LIA ELAs in the Julian Alps. In the Canin area 25 km west, the ELA was established at 2225 m (AAR 0.67) which is 252 m higher than in Krnica. Only 5 km south-east on Triglav, the ELA during LIA was at 2436 m, which leads to a difference of 463 m. Recent studies conducted in the Julian Alps (Colucci et al., 2015; Colucci, 2016; Colucci and Žebre, 2016) have shown that the reconstructed ELAs during LIA are largely dependent on precipitation and solar radiation, the latter strictly reliant on slope aspect. Therefore, such large differences in ELA are probably to be found in the significant avalanche activity and in the extreme summer shading in the Krnica Valley. Moreover, windblown snow accumulation in the main cirque is probably also a very important source of snow-recharge. This is especially true during major winter storms coming from the south and advecting large moisture from the Adriatic Sea. The avalanche ratio (V/A), defined as the contribution from avalanches by determining the total avalanche susceptible area and the total glacier area (Hughes, 2010, 2008), was calculated to 1.1 for the Krnica glacier and is higher than for the Canin (0.8) and the Triglav (0.9) glaciers at the LIA stage

(Colucci, 2016). In other avalanche-dominated small glaciers of the Julian Alps, such as Montasio, where the LIA V/A ratio of 1.8 has been calculated, the ELA was depressed to about 1950 m, therefore very similar to the Krnica Valley. Other ice patches nowadays still active in the area of Ponca and Dovski Križ (ca. 4 km NE) show median elevations close to 2200 m (Colucci, 2016).

The Krnica Stage 1 is characterized by two well-preserved sub-parallel and juxtaposed frontal moraine ridges (Figure 4a) that have already been described by Kunaver (1999) as the result of the "last stage" of the glacier. This "last stage" has been supposed by Colucci (2016) as belonging to the LIA maximum owing the lack of soil development in the moraine system, suggesting recent surface exposure, and according to other similar existing features in the Julian Alps at similar elevation (e.g. Montasio, median elevation 1906 m; Prevala, median elevation 1862 m) for which direct photographic evidence exist. It is unlikely that these moraines are older, but they might be superimposed on the Late Subboreal (2.5 – 4.2 ka BP) moraines. The latter glacier advance has been recognized in some Western and Central Alpine valleys (e.g. Delin and Orombelli, 2005; Hormes et al., 2001; Federici et al., 2016), but is still missing from the eastern alpine glacial chronology. The innermost ridge may have formed during the 1910–1920 advancing phase which is well represented in the Julian Alps on the Canin-Cergnala (46°22'46.43"S, 13°30'49.11"V; 22 km SWW) and Montasio-Jof Fuart (46°26'24.59"S, 13°26'18.54"V; 28 km NWW) sectors. Such ridges are rather a result of moving ice of a small ice body similar to other dynamic firn/ice bodies at present existing in other areas of the Mediterranean mountains (e.g. Hughes and Woodward, 2017) as well as in the southeastern Alps (Colucci, 2016; Colucci and Žebre, 2016). Nevertheless, the presence of clast-supported sediments with sub-angular clasts also indicates that some debris was probably sliding and rolling down over the LIA ice body reaching the frontal ridge. This is a typical behaviour already observed in some densely packed snow and firn bodies, produced in maritime periglacial climates with heavy winter snowfall and rapid snow-firn conversion, able to push and shape the frontal debris. Fast snow metamorphism in the Krnica cirque can be inferred by the estimated density values obtained with the geophysical survey (24th June 2015) equal to 450 kg m^{-3} in the shallowest layer. Such features with the presence of a thick ice deposit are generally defined as ice patches of nival origin (Serrano et al., 2011). They take place thanks to progressive snow accumulation and *firn* metamorphisms leading to the inception of a small glacier when its mass is sufficient to allow for flow and internal motion (*anaglacial* phase). On the contrary ice patches of glacial origin develop from a shrinking glacier when this reaches a mass too small for internal motion and its flow ceases (*kataglacial* phase). In the case of Krnica cirque a combination of *kataglacial* and *anaglacial* processes seem to alternately operate, therefore leading to the inception of dynamically active nival ice patches, but where the relict-ice fraction is gradually decreasing.

The possible presence of a thick layer of relict-ice imaged by the GPR survey performed in the summer 2015 poses an interesting speculation on the real nature of this glacial body. The topography of the moraine complex is remarkable, especially if observed from down valley, and a great altitude difference (ca. 30 m) between the two sides of the moraine complex implies the presence of a thick, debris-rich ice deposits (Figure 4a). The occurrence of relict thick glacier ice deposits located at similar elevations has been already reported also from other ice patches in the southeastern Alps (Carturan et al., 2014; Colucci et al., 2015; Forte et al., 2014a), such as the case of the Prevala, the Montasio West and the Canin East. This is important because the Krnica glacier represents a much larger and thicker ice body if compared with the disappearing but iconic Triglav glacier, now reduced to a thin plate of dead ice and classified as an ice patch of glacial origin with no dynamics (Del Gobbo et al., 2016). Thick debris deposits of the Krnica ice patch have the effect of limiting the summer melting, thus slowing down a fast disappearance of such small ice bodies. A similar situation has also been observed in the Atlantic high mountain karst environment of Picos de Europa (NW Spain), where a buried ice patch, a remnant of the LIA glacier, still exists (Ruiz-Fernández et al., 2017). In this case the role of snow cover, strongly influenced by topography, exerts large importance in regulating the ground thermal regime and even if no permafrost regime was detected, permanent frozen conditions much deeper in the ground were inferred. The evolution of this buried ice body has been seen as largely dependent on water infiltration through the clastic material when no snow is present over the debris. This leads to penetration of the thermal wave deep in the ground that is able to trigger the degradation of the frozen sediments (Gómez-Ortiz et al., 2014). This mechanism is of course more effective if the infiltrating water is warmer and abundant. In this regards longer and hotter summers and the occurrence of more intense precipitation later in autumn under climate change scenarios, will possibly lead to a faster reduction of the buried ice of the Krnica cirque in the next decades. This has been recently observed in the Julian Alps already occurring in cave ice deposits where extreme warm precipitation at high altitudes in the late autumn triggered abrupt reductions of such underground ice bodies (Colucci et al., 2016).

At the top of the debris covering the ice patch, other two smaller, irregularly shaped ridges, composed of clast-supported deposits with sub-angular clasts, are present in the Krnica cirque (Figure 5). These features are probably more consistent with a snow-avalanche dominated formational process as described by Matthews et al. (2011) rather than originating from glacial processes. This is further confirmed by the distance of less than 30-70 m between the ridges and the talus foot slope, seen by Ballantyne and Benn (1994) as the lower limit for triggering morphologies influenced by moving ice, rather than a simple gravity-fed debris supply across the topographic surface of the snow patch.

Three hundred metres down valley from the LIA moraine, the Stage 2 glacier (Figures 4b, 7) formed another frontal moraine, which is characterised by being very blocky with large boulders up to 10 m in diameter. With the reconstructed ELA at 1923 m (50 m lower than LIA) this stage may be linked to the early Holocene cold phase (10.5 ka) (Haas et al., 1998; Solomina et al., 2015) recognized in some of the valleys in the northern Alps (e.g. Schindelwig et al., 2011; Schimmelpfennig et al., 2014) with 75 m of ELA depression versus LIA ELA (Ivy-Ochs, 2015). This is also in agreement with the studies on speleothems from the eastern Alps reported by Frisia et al. (2005) and Belli et al. (2013) indicating two periods of colder and drier conditions between ca. 10.8 +/- 0.2 ka and 10.1 +/- 0.2 ka. Moreover, it was inferred from the analysis of fossil chironomid (Heiri et al., 2004) that July temperatures in the Alps fell ca. 1°C between 10.7 and 10.5 cal ka BP. Other works also indicate a phase of widespread glacier advance in the Alps with stadial moraines dated at 10.5 ka by using 10Be exposure ages (Ivy-Ochs et al., 2009). The ELA lowering observed in the Krnica Valley may be evaluated by using a simple relation set by Kuhn (1981) which suggests a drop of summer temperature of 0.8°C or an increase in annual accumulation of 400 mm a^{-1} for having a ΔELA of -100 m. Also Ohmura et al. (1992) quantified that a temperature change of 1.0°C would be equivalent to a change in precipitation of 300-400 mm. In these regards smaller precipitation could have resulted in a minor ELA depression compared to the western and northern Alps, especially owing to the low elevation of this glacier. This would be confirmed looking at the distinct Younger Dryas ELAs spatial pattern reconstructed in the Alps, triggered by the supposed more westerly to north-westerly atmospheric circulation pattern affecting winters of Central Europe and the Alps at that time (Kerschner et al., 2000). This was able to increase the amount of precipitation by about 10% in the exposed areas (western and northern side of the Alps) and reducing it up to 30% in the more sheltered inner alpine areas, such as in the case of Krnica. After the earliest Holocene cold phase (10.5 ka) no considerably colder and/or drier conditions compared to the present day were reconstructed in the southeastern Alps. Climatic conditions in the Alps between about 10.5 ka and 3.3 ka were probably favourable only to minor glacier advances (Solomina et al., 2015) when only small glaciers (less than 1 km^2) may have formed down to positions close to the LIA expansion. These were recognized in some valleys of the Central and Western Alps (e.g. Deline and Orombelli, 2005; Federici et al., 2016; Hormes et al., 2001; Nicolussi and Schlüchter, 2012). Therefore, the Stage 2 could be alternatively linked also to the 8.2 ka cold event, or even to the Preboreal Oscillation (11.5 ka), although for Central Alps the ELA depression respect to the LIA ELA for the latter advance is 120 m, which doesn't match quite well with our ELA depression calculation, which is 50 m for the Stage 2 versus Stage 1. The 8.2 ka cold event is the next best alternative for the 10.5 ka, but any further speculation on the basis of the available dataset is pointless.

A much colder and drier period took place in the eastern Alps also between 12.8 +/- 0.3 ka and 11.9 ka (Belli et al., 2013; Frisia et al., 2005). According to findings in the central Alps and Maritime Alps the Younger Dryas ELA depression respect to LIA ELA was found to be of 250-350 m (Federici et al., 2008; Ivy-Ochs, 2015) and 180-450 m (Ivy-Ochs et al., 2008). In this respect, the Stage 3 (Figures 4c, 7, 9) with the ELA at 1812 m (161 m lower than LIA), may be therefore associated with this climatic event corresponding to the Younger Dryas advance, taking into account same arguments discussed for the Stage 2, mainly the supposed change in the atmospheric circulation pattern. Supporting this interpretation, in the Italian Julian Alps some overgrown moraines at ca. 1850 m and ca. 1950 m (Canin) and at ca. 1800 m (Montasio) with the presence of boulders marked by rillen karren on the surface have been tentatively assigned to the Egesen stadial (equivalent to the Younger Dryas cold period) (Tintor and Andrič, 2014) and to the Lateglacial (Carturan et al., 2013). This stage can be alternatively linked also to the Preboreal Oscillation (11.5 ka), for which a 120 m of ELA depression versus LIA ELA was calculated in the northern-central Alps (Ivy-Ochs, 2015). However, it is unlikely that these moraines would be of Preboreal age since the next generation of well-expressed moraines below these ascribed to the Stage 3 are too low in altitude and not enough fresh in appearance to be of Younger Dryas age.

6. Conclusions

The post-LGM glacial evolution in the southeastern Alps is still ambiguous and scarcely investigated from the sedimentological and chronological point of view. This paper is the first step towards a comprehensive study of glacial landforms occurring in this key area of Lateglacial to Holocene glacial advances. The Krnica Valley in the Julian Alps of Slovenia hosts very well-preserved glacial deposits despite of widespread destructive mass-movement and fluvial processes at present influencing the geomorphological setting of the Valley. Three geomorphologically and sedimentologically well defined glacial stages were recognized in the upper Krnica Valley. This was done taking into account the glacier topography reconstruction and the estimation of ELAs which linked the Krnica stages seen on the field to the three Lateglacial-Holocene main cold climatic phases generally recognised in the Alps. Results hint at the LIA age for the Stage 1 (ELA at 1973 m a.s.l.), early Holocene age (10.5 ka) for the Stage 2 (ELA at 1923 m a.s.l.) (or alternatively 8.2 ka cold event) and Younger Dryas (or alternatively Preboreal Oscillation, 11.5 ka) for the Stage 3 (ELA at 1812 m a.s.l.). Apart from palaeoglaciers, the presence of buried ice below the debris partially covered by permanent snow patches present in the Krnica cirque, was also evidenced up-valley from a set of LIA moraines. This relict glacier ice was imaged by GPR and gives important indications on the microclimate of this area and its possible evolution with the ongoing climate warming.

The current research presents a first step of an ongoing research and should be complemented in the future with geomorphological mapping and sedimentological characterization of lower valley and, even more important, with geochronological studies to confirm the proposed timing of glacial stages in the entire Krnica area. This should constrain the timing of the post-LGM glacial advances for the first time in the Julian Alps giving important implications for the climate of the SE Alps at that time.

Acknowledgements

We thank two anonymous reviewers for their constructive comments and suggestions which improved the quality of this paper. We also acknowledge the financial support from the Slovenian Research Agency (research core funding No. P1-0011, Program Regional Geology).

Author contribution

RRC and MŽ conceived the study and wrote the manuscript. MŽ, EK and EF realized the figures and US acquired the images with the drone. US and EK contributed to the text for the regional and geomorphological settings. EF collected and analysed the geophysical data and wrote the related chapter of methods and results. All the authors took part to the fieldworks and participated in the discussion revising the final version of the manuscript.

References

ARSO (Slovenian Environment Agency), 2017. http://www.arso.gov.si/en/ (Accessed 9 February 2017).
ARSO LIDAR (Slovenian Environment Agency LiDAR), 2016. http://gis.arso.gov.si/evode/profile.aspx?id=atlas_voda_Lidar@Arso (Accessed 10 December 2016).
Badjura, R., 1913. Na Triglav, v kraljestvo Zlatorogovo! : (kažipot na Triglav) : 27 fotografičnih posnetkov, 1 zemljevid, 3 načrti. H. Badiura, Ljubljana, pp. 108.
Ballantyne, C.K., Benn, D.I., 1994. Glaciological Constraints on Protalus Rampart Development. Permafr. Periglac. Process. 5, 145–153. doi:10.1002/ppp.3430050304
Bavec, M., Tulaczyk, S.M., Mahan, S.A., Stock, G.M., 2004. Late Quaternary glaciation of the Upper Soča River Region (Southern Julian Alps, NW Slovenia). Sediment. Geol. 165, 265–283. doi:10.1016/j.sedgeo.2003.11.011
Bavec, M., Verbič, T., 2011. Glacial history of Slovenia, Developments in Quaternary Science. doi:10.1016/B978-0-444-53447-7.00029-5
Belli, R., Frisia, S., Borsato, A., Drysdale, R., Hellstrom, J., Zhao, J.X., Spötl, C., 2013. Regional climate variability and ecosystem responses to the last deglaciation in the northern hemisphere from stable isotope data and calcite fabrics in two northern Adriatic stalagmites. Quat. Sci. Rev. 72, 146–158. doi:10.1016/j.quascirev.2013.04.014
Benn, D.I., Ballantyne, C.K., 2005. Palaeoclimatic reconstruction from Loch Lomond Readvance glaciers in the West Drumochter Hills, Scotland. J. Quat. Sci. 20, 577–592. doi:10.1002/jqs.925
Benn, D.I., Hulton, N.R.J., 2010. An ExcelTM spreadsheet program for reconstructing the surface profile of former mountain glaciers and ice caps. Comput. Geosci. 36, 605–610. doi:10.1016/j.cageo.2009.09.016
Carturan, L., Baldassi, G.A., Bondesan, A., Calligaro, S., Carton, A., Cazorzi, F., Dalla Fontana, G., Francese, R., Guarnieri, A., Milan, N., Moro, D., Tarolli, P., 2013. Current Behaviour and Dynamics of the Lowermost Italian Glacier (Montasio Occidentale, Julian Alps). Geogr. Ann. Ser. A, Phys. Geogr. 95, 79–96. doi:10.1111/geoa.12002
Fontana, A., Mozzi, P., Bondesan, A., 2008. Alluvial megafans in the Venetian–Friulian Plain (north-eastern Italy): Evidence of sedimentary and erosive phases during Late Pleistocene and Holocene Quaternary International, 189, 71–90
Carturan, L., Baroni, C., Carton, A., Cazorzi, F., Fontana, G.D., Delpero, C., Salvatore, M.C., Seppi, R., Zanoner, T., 2014. Reconstructing Fluctuations of La Mare Glacier (Eastern Italian Alps) in the Late Holocene: New Evidence for a Little Ice Age Maximum Around 1600 AD. Geogr. Ann. Ser. A, Phys. Geogr. 96, 287–306. doi:10.1111/geoa.12048

Celarc, B., Goričan, Š., Kolar-Jurkovšek, T., 2013. Middle Triassic carbonate-platform break-up and formation of small-scale half-grabens (Julian and Kamnik–Savinja Alps, Slovenia). Facies, 59, 583–610. doi: 10.1007/s10347-012-0326-0
Celarc, B., Kolar-Jurkovšek, T., 2008. The Carnian-Norian basin-platform system of the Martuljek Mountain Group (Julian Alps, Slovenia): progradation of the Dachstein carbonate platform. Geol. Carphatica 59, 211–224.
Colucci, R.R., Žebre, M., 2016. Late Holocene evolution of glaciers in the southeastern Alps. J. Maps. doi:10.1080/17445647.2016.1203216
Colucci, R.R., 2016. Geomorphic influence on small glacier response to post Little Ice Age climate warming: Julian Alps, Europe. Earth Surf. Process. Landforms 41, 1227–1240. doi:10.1002/esp.3908
Colucci, R.R., Boccali, C., Žebre, M., Guglielmin, M., 2016. Rock glaciers, protalus ramparts and pronival ramparts in the south-eastern Alps. Geomorphology 269, 112–121. doi:10.1016/j.geomorph.2016.06.039
Colucci, R.R., Fontana, D., Forte, E., Potleca, M., Guglielmin, M., 2016. Response of ice caves to weather extremes in the southeastern Alps, Europe. Geomorphology 261, 1–11. doi:10.1016/j.geomorph.2016.02.017
Colucci, R.R., Forte, E., Boccali, C., Dossi, M., Lanza, L., Pipan, M., Guglielmin, M., 2015. Evaluation of Internal Structure, Volume and Mass of Glacial Bodies by Integrated LiDAR and Ground Penetrating Radar Surveys: The Case Study of Canin Eastern Glacieret (Julian Alps, Italy). Surv. Geophys. 36, 231–252. doi:10.1007/s10712-014-9311-1
Colucci, R.R., Guglielmin, M., 2015. Precipitation–temperature changes and evolution of a small glacier in the southeastern European Alps during the last 90 years. Int. J. Climatol. 35, 2783–2797. doi:10.1002/joc.4172
Colucci, R.R., Monegato, G., Žebre, M., 2014. Glacial and proglacial deposits of the resia valley (ne Italy): New insights on the onset and decay of the last alpine glacial maximum in the Julian Alps. Alp. Mediterr. Quat. 27, 85¬104.
Daniels, D., 2004. Ground Penetrating Radar. Vol. 15 of IEE Radar, Sonar, Navigation and Avionics Series, The Institution of Electrical Engineers, MPG Books, 2nd edition, 300pp., ISBN: 0-85296-862-0.
Del Gobbo, C., Colucci, R.R., Forte, E., Triglav, M., Zorn, M., 2016. The Triglav glacier (Eastern Alps, Slovenia): Volume estimation, internal characterization and 2000-2013 temporal evolution by means of Ground Penetrating Radar measurements. Pure and Applied Geophysics 173, 2753–2766. doi:10.1007/s00024-016-1348-2
Deline, P., Orombelli, G., 2005. Glacier fluctuations in the western Alps during the Neoglacial, as indicated by the Miage morainic amphitheatre (Mont Blanc massif, Italy). Boreas 34, 456–467. doi:10.1111/j.1502-3885.2005.tb01444.x
Državna topografska karta Republike Slovenije 1:25.000. 041, Kranjska Gora, 1998.
Ehlers, J., Gibbard, P.L., 2004. Quaternary Glaciations Extent and Chronology - Part I: Europe, Developments in Quaternary Sciences. doi:10.1016/S1571-0866(04)80056-3
Federici, P.R., Granger, D.E., Pappalardo, M., Ribolino, A., Spagnolo, M., Cyr, A.J., 2008. Exposure age dating and Equilibrium Line Altitude reconstruction of an Egesen moraine in the Maritime Alps, Italy. Boreas 37, 245–253. doi:10.1111/j.1502-3885.2007.00018.x
Federici, P.R., Ribolini, A., Spagnolo, M., 2016. Glacial history of the Maritime Alps from the Last Glacial Maximum to the Little Ice Age. Geol. Soc. London, Spec. Publ. 433. doi:10.1144/SP433.9
Forte, E., Dossi, M., Colucci, R.R., Pipan, M., 2013. A new fast methodology to estimate the density of frozen materials by means of common offset GPR data. J. Appl. Geophys. 99, 135–145. doi:http://dx.doi.org/10.1016/j.jappgeo.2013.08.013
Forte, E., Dossi, M., Fontana, M.C., Colucci, R.R., 2014a. 4-D quantitative GPR analyses to study the summer mass balance of a glacier: a case history. Proc. 15th Int. Conf. Gr. Penetrating Radar. doi:10.1109/ICGPR.2014.6970444
Forte, E., Dossi, M., Pipan, M., Colucci, R.R., 2014b. Velocity analysis from common offset GPR data inversion: theory and application to synthetic and real data. Geophys. J. Int. 197, 1471–1483.

Frisia, S., Borsato, A., Spötl, C., Villa, I., Cucchi, F., 2005. Climate variability in the SE Alps of Italy over the past 17 000 years reconstructed from a stalagmite record. Boreas 34, 445–455. doi:10.1080/03009480500231336
Gams, I., 1961. Snežišča v Julijskih Alpah. Geogr. Zb. 6, 241-269.
Gams, I., 1992. Prispevek k mladokvartarni geomorfologiji v Zgornjesavski dolini = A contribution to the young Quaternary geomorphology in the Upper Sava Valley. Geogr. Zb. 32,5-49.
Gómez-Ortiz, A., Oliva, M., Salvador-Franch, F., Salvà-Catarineu, M., Palacios, D., de Sanjosé-Blasco, J.J., Tanarro-García, L.M., Galindo-Zaldívar, J., Sanz de Galdeano, C., 2014. Degradation of buried ice and permafrost in the Veleta cirque (Sierra Nevada, Spain) from 2006 to 2013 as a response to recent climate trends. Solid Earth 5, 979–993. doi:10.5194/se-5-979-2014
Gross, G., Kerschner, H., Patzelt, G., 1977. Methodische Untersuchungen über die Schneegrenze in alpinen Gletschergebieten. Zeitschrift für Gletscherkd. und Glazialgeol. 12, 223–251.
GURS, 1992. Temeljni topografski načrti merila 1 : 5.000 (TTN 5). URL http://www.e-prostor.gov.si/ (Accessed 10 December 2016).
GURS, 1993. Temeljni topografski načrti merila 1 : 10.000 (TTN 10). URL http://www.e-prostor.gov.si/ (Accessed 10 December 2016).
GURS, 1998-2015. Ortofoto. URL http://www.e-prostor.gov.si/ (accessed 12.10.16).
Haas, J.N., Richoz, I., Tinner, W., Wick, L., 1998. Synchronous Holocene climatic oscillations recorded on the Swiss Plateau and at timberline in the Alps. The Holocene 8, 301–309. doi:10.1191/095968398675491173
Heiri, O., Tinner, W., Lotter, A.F., 2004. Evidence for cooler European summers during periods of changing meltwater flux to the North Atlantic. Proc. Natl. Acad. Sci. U. S. A. 101, 15285–15288. doi:10.1073/pnas.0406594101
Hormes, A., Müller, B.U., Schlüchter, C., 2001. The Alps with little ice: evidence for eight Holocene phases of reduced glacier extent in the Central Swiss Alps. The Holocene 11, 255–265. doi:10.1191/095968301675275728
Hughes, P.D., 2008. Response of a montenegro glacier to extreme summer heatwaves in 2003 and 2007. Geogr. Ann. Ser. A, Phys. Geogr. 90, 259–267. doi:10.1111/j.1468-0459.2008.00344.x
Hughes, P.D., 2010. Little Ice Age glaciers in the Balkans: Low altitude glaciation enabled by cooler temperatures and local topoclimatic controls. Earth Surf. Process. Landforms 35, 229–241. doi:10.1002/esp.1916
Hughes, P.D., Woodward, J.C., 2017. Quaternary glaciation in the Mediterranean mountains: a new synthesis. Geol. Soc. London, Spec. Publ. 433, 1–23. doi:10.1144/SP433.14
Hughes, P.D., Woodward, J.C., van Calsteren, P.C., Thomas, L.E., Adamson, K.R., 2010. Pleistocene ice caps on the coastal mountains of the Adriatic Sea. Quat. Sci. Rev. 29, 3690–3708. doi:10.1016/j.quascirev.2010.06.032
Ivy-Ochs, S., 2015. Glacier variations in the European Alps at the end of the last glaciation. Cuad. Investig. Geográfica 41, 295–315.
Ivy-Ochs, S., Kerschner, H., Maisch, M., Christl, M., Kubik, P.W., Schlüchter, C., 2009. Latest Pleistocene and Holocene glacier variations in the European Alps. Quat. Sci. Rev. 28, 2137–2149. doi:10.1016/j.quascirev.2009.03.009
Ivy-Ochs, S., Kerschner, H., Reuther, A., Preusser, F., Heine, K., Maisch, M., Kubik, P.W., Schlüchter, C., 2008. Chronology of the last glacial cycle in the European Alps. J. Quat. Sci. 23, 559–573. doi:10.1002/jqs.1202
Jamšek Rupnik, P., Benedetti, L., Bavec, M., Vrabec, M.. 2012. Geomorphic indicators of Quarternary activity of the Sava fault between Golnik and Preddvor. RMZ - Materials and geoenvironment, 59, 2/3, 299-314.
Jol, H.M. (Ed.), 2009. Ground penetrating radar : theory and applications. Elsevier Science, Amsterdam, Netherlands; Oxford, UK.
Jurkovšek, B., 1987a. Tolmač listov Beljak in Ponteba : Osnovna geološka karta Republike Slovenije in Republike Hrvaške : 1: 100 000 : L 33-51, L 33-52. Zvezni geološki zavod, Beograd.
Jurkovšek, B., 1987b. Osnovna geološka karta SFRJ. L 33-52, L 33-51, Beljak in Ponteba.

Kerschner, H., Kaser, G., Sailer, R., 2000. Alpine Younger Dryas glaciers as palaeo-precipitation gauges. Ann. Glaciol. 31, 80-84.
Kuhn, M., 1981. Climate and Glaciers. Sea Level, Ice, and Climatic Change, in: Proceedings of the Canberra Symposium, December 1979. IAHS 131. pp. 3–20.
Kunaver, J., 1999. Geomorfološki razvoj doline Krnice in njene zadnje poledenitve. Sonaravni razvoj v slovenskih Alpah in sosedstvu, Dela 13, 63-75.
Looyenga, H., 1965. Dielectric constants of heterogeneous mixtures. Physica, 31, 401–406.
Matthews, J. a., Shakesby, R. a., Owen, G., Vater, A.E., 2011. Pronival rampart formation in relation to snow-avalanche activity and Schmidt-hammer exposure-age dating (SHD): Three case studies from southern Norway. Geomorphology 130, 280–288. doi:10.1016/j.geomorph.2011.04.010
Melik, A., 1955. Nekaj glacioloških opažanj iz zgornje Doline. Geogr. Zb. 3, 299-318.
Monegato, G., 2012. Local glaciers in the Julian Prealps (NE Italy) during the Last Glacial Maximum. Alp. Mediterr. Quat. 25, 5–14.
Monegato, G., Scardia, G., Hajdas, I., Rizzini, F., Piccin, A., 2017. The Alpine LGM in the boreal ice-sheets game. Scientific Reports 7, 2078.
Monegato, G., Ravazzi, C., Donegana, M., Pini, R., Calderoni, G., Wick, L., 2007. Evidence of a two-fold glacial advance during the last glacial maximum in the Tagliamento end moraine system (eastern Alps). Quat. Res. 68, 284–302. doi:10.1016/j.yqres.2007.07.002
Moulin, A., Benedetti, L., Rizza, M., Jamšek Rupnik, P., Gosar, A., Bourlès, D., Keddadouche, K., Aumaître, G., Arnold, M., Guillou, V., Ritz, J. F., 2016. The Dinaric Fault System: large-scale structure, rates of slip and Plio-Pleistocene evolution of the transpressive northeastern boundary of the Adria microplate. Tectonics, 10, 35, 2258-2292. doi: 10.1002/2016TC004188.
Nicolussi, K., Schlüchter, C., 2012. The 8.2 ka event – calendar-dated glacier response in the Alps. Geology 40, 819–822.
Norbiato, D., Borga, M., Sangati, M., Zanon, F., 2007. Regional frequency analysis of extreme precipitation in the eastern Italian Alps and the August 29, 2003 flash flood. J. Hydrol. 345, 149–166. doi:10.1016/j.jhydrol.2007.07.009
Ohmura, A., Kasser, P., Funk, M., 1992. Climate at the equilibrium line of glaciers. J. Glaciol. 38, 397-411.
Pavlovec, R., 1961. Zasuta dolina Pišnice pri Kranjski Gori. Proteus 24, 148-149.
Pellitero, R., Rea, B.R., Spagnolo, M., Bakke, J., Hughes, P., Ivy-Ochs, S., Lukas, S., Ribolini, A., 2015a. A GIS tool for automatic calculation of glacier equilibrium-line altitudes. Comput. Geosci. 82, 55–62. doi:10.1016/j.cageo.2015.05.005
Pellitero, R., Rea, B.R., Spagnolo, M., Bakke, J., Ivy-Ochs, S., Frew, C.R., Hughes, P., Ribolini, A., Lukas, S., Renssen, H., 2016. GlaRe, a GIS tool to reconstruct the 3D surface of palaeoglaciers. Comput. Geosci. 94, 77–85. doi:10.1016/j.cageo.2016.06.008
Penck, A., Brückner, E., 1901/1909. Die Alpen im Eiszeitalter. Tauchnitz, Leipzig.
Porter, S.C., 1975. Equilibrium-line altitudes of late Quaternary glaciers in the Southern Alps, New Zealand. Quat. Res. 5, 27–47. doi:10.1016/0033-5894(75)90047-2
Porter, S.C., 2001. Snowline depression in the tropics during the last glaciation. Quat. Sci. Rev. 20, 1067-1091. doi:10.1016/S0277-3791(00)00178-5
Poto, L., Gabrieli, J., Crowhurst, S.J., Applebey, P.G., Ferretti, P., Surian, N., Cozzi, G., Zaccone, C., Turetta, C., Pini, R., Kehrwald, N., Barbante, C., 2013. The first continuous Late Glacial – Holocene peat bog multi-proxy record from the Dolomites (NE italian Alps). Quaternary International, 306, 71-79
Reitner, J.M., 2007. Glacial dynamics at the beginning of Termination I in the Eastern Alps and their stratigraphic implications. Quaternary International 164/165, 64-84
Reitner, J.M., 2012. Challenges in deciphering the Last Glacial Cycle in Eastern Alps: Examples from the Drau glacier system. Quaternary International, 279/280, 398
Ruiz-Fernández, J., Oliva, M., Hrbáček, F., Vieira, G., García-Hernández, C., 2017. Soil temperatures in an Atlantic high mountain environment: The Forcadona buried ice patch (Picos de Europa, NW Spain). CATENA 149, 637–647. doi:http://dx.doi.org/10.1016/j.catena.2016.06.037

Schimmelpfennig, I., Schaefer, J.M., Akçar, N., Koffman, T., Ivy-Ochs, S., Schwartz, R., Finkel, R.C., Zimmerman, S., Schlüchter, C., 2014. A chronology of Holocene and Little Ice Age glacier culminations of the Steingletscher, Central Alps, Switzerland, based on high-sensitivity beryllium-10 moraine dating. Earth Planet. Sci. Lett. 393, 220–230. doi:https://doi.org/10.1016/j.epsl.2014.02.046

Schindelwig, I., Akçar, N., Kubik, P.W., Schlüchter, C., 2012. Lateglacial and early Holocene dynamics of adjacent valley glaciers in the Western Swiss Alps. J. Quat. Sci. 27, 114–124. doi:10.1002/jqs.1523

Serrano, E., González-Trueba, J.J., Sanjosé, J.J., Del Río, L.M., 2011. Ice patch origin, evolution and dynamics in a temperate high mountain environment: the Jou Negro, Picos de Europa (NW Spain). Geogr. Ann. Ser. A, Phys. Geogr. 93, 57–70. doi:10.1111/j.1468-0459.2011.00006.x

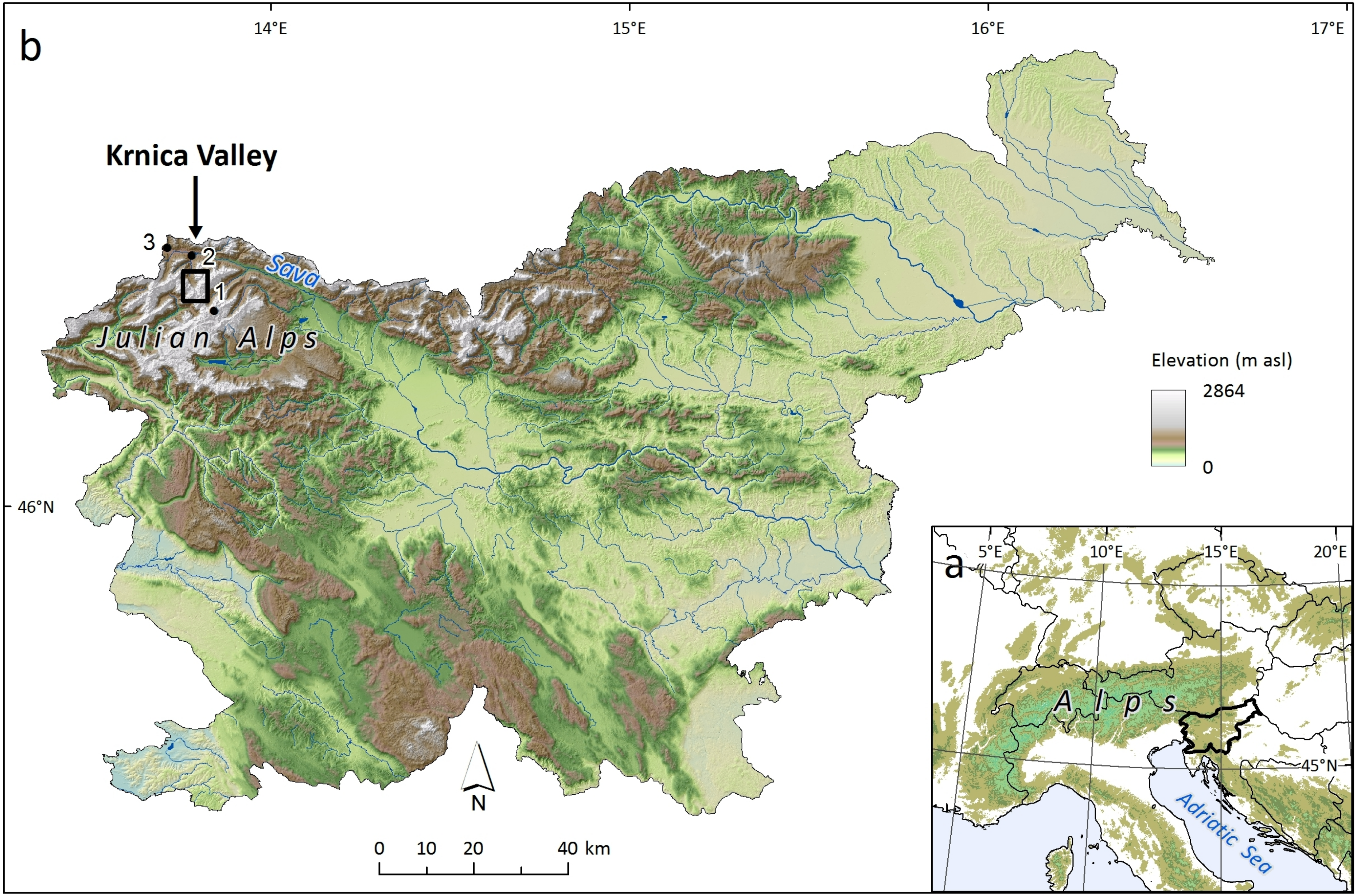
Solomina, O.N., Bradley, R.S., Hodgson, D.A., Ivy-Ochs, S., Jomelli, V., Mackintosh, A.N., Nesje, A., Owen, L.A., Wanner, H., Wiles, G.C., Young, N.E., 2015. Holocene glacier fluctuations. Quat. Sci. Rev. 111, 9-34. doi:10.1016/j.quascirev.2014.11.018

Tintor, W., Andrič, M., 2014. Lateglacial studies in the western valleys of the Italian Julian Alps and in the Koritnica valley. Acta Geogr. Slov. 54, 7-20.

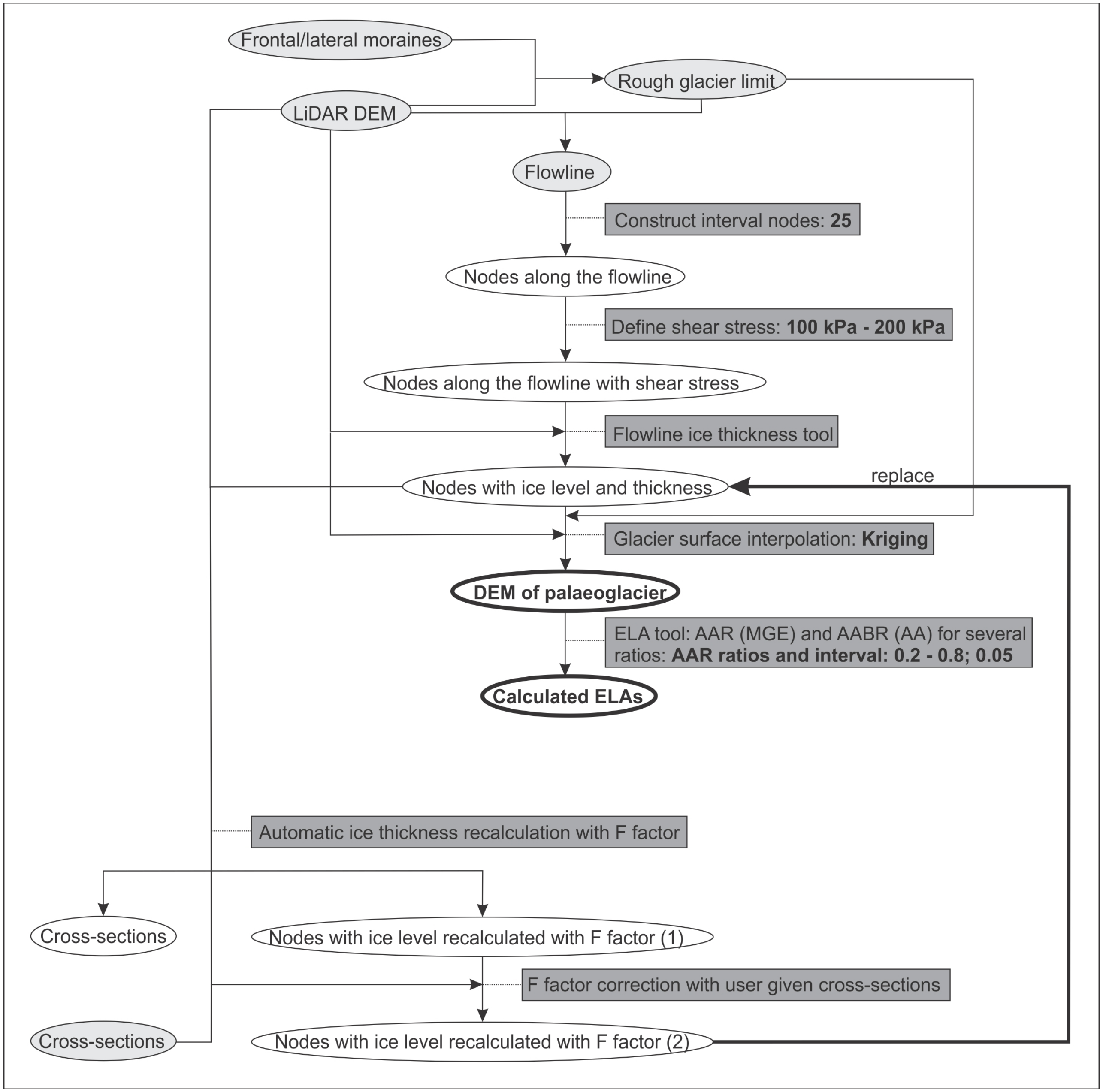
Tošić, I., Zorn, M., Ortar, J., Unkašević, M., Gavrilov, M.B., Marković, S.B., 2016. Annual and seasonal variability of precipitation and temperatures in Slovenia from 1961 to 2011 Atmospheric Research 168,220–233

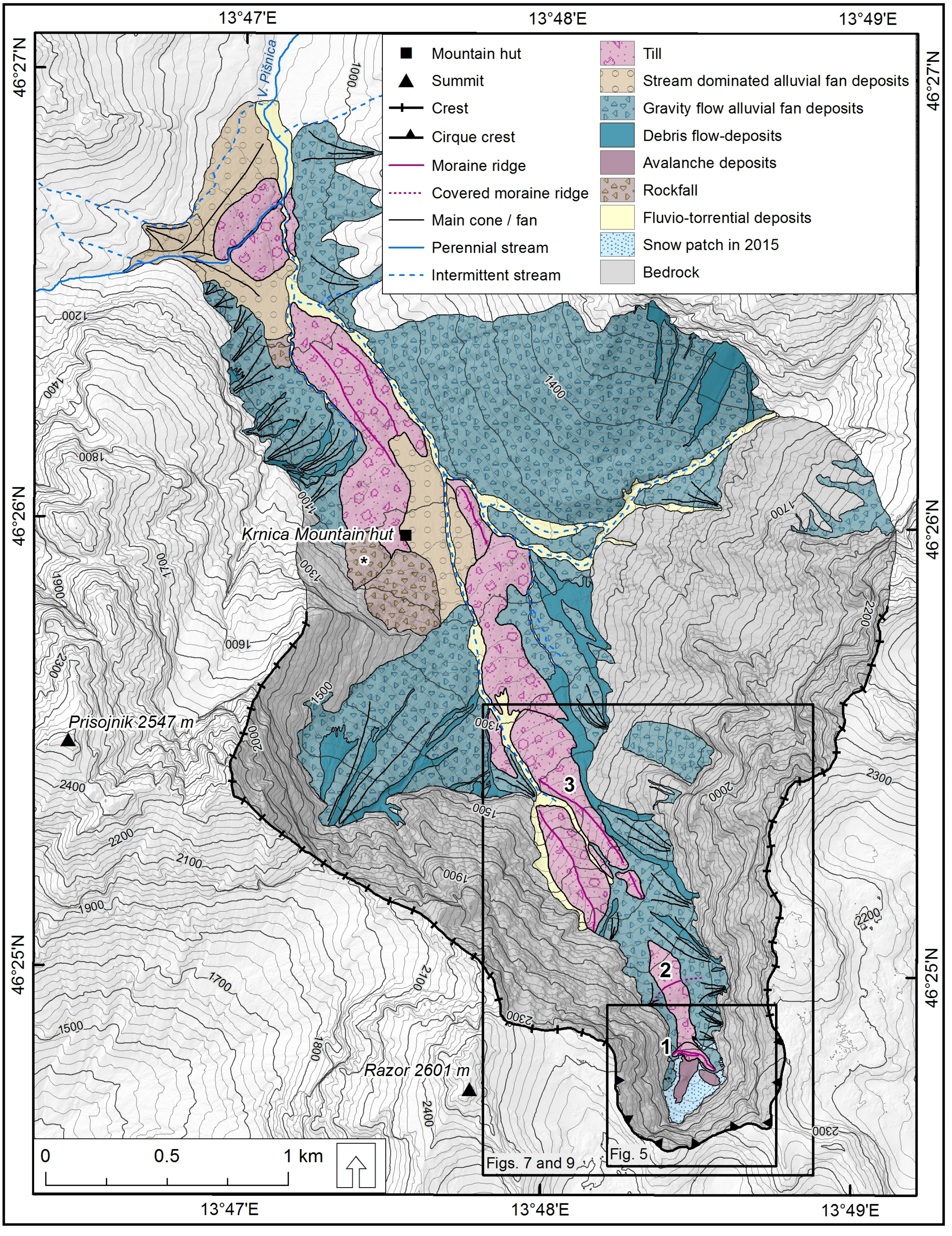
Van Husen, D., 1997. LGM and Late-Glacial fluctuations in the Eastern Alps. Quaternary International, 38/39, 109-118.

Zhao, W., Forte, E., Colucci, R.R., Pipan, M., 2016. High-resolution glacier imaging and characterization by means of GPR attribute analysis. Geophysical Journal International 206, 1366-1374. doi:10.1093/gji/ggw208

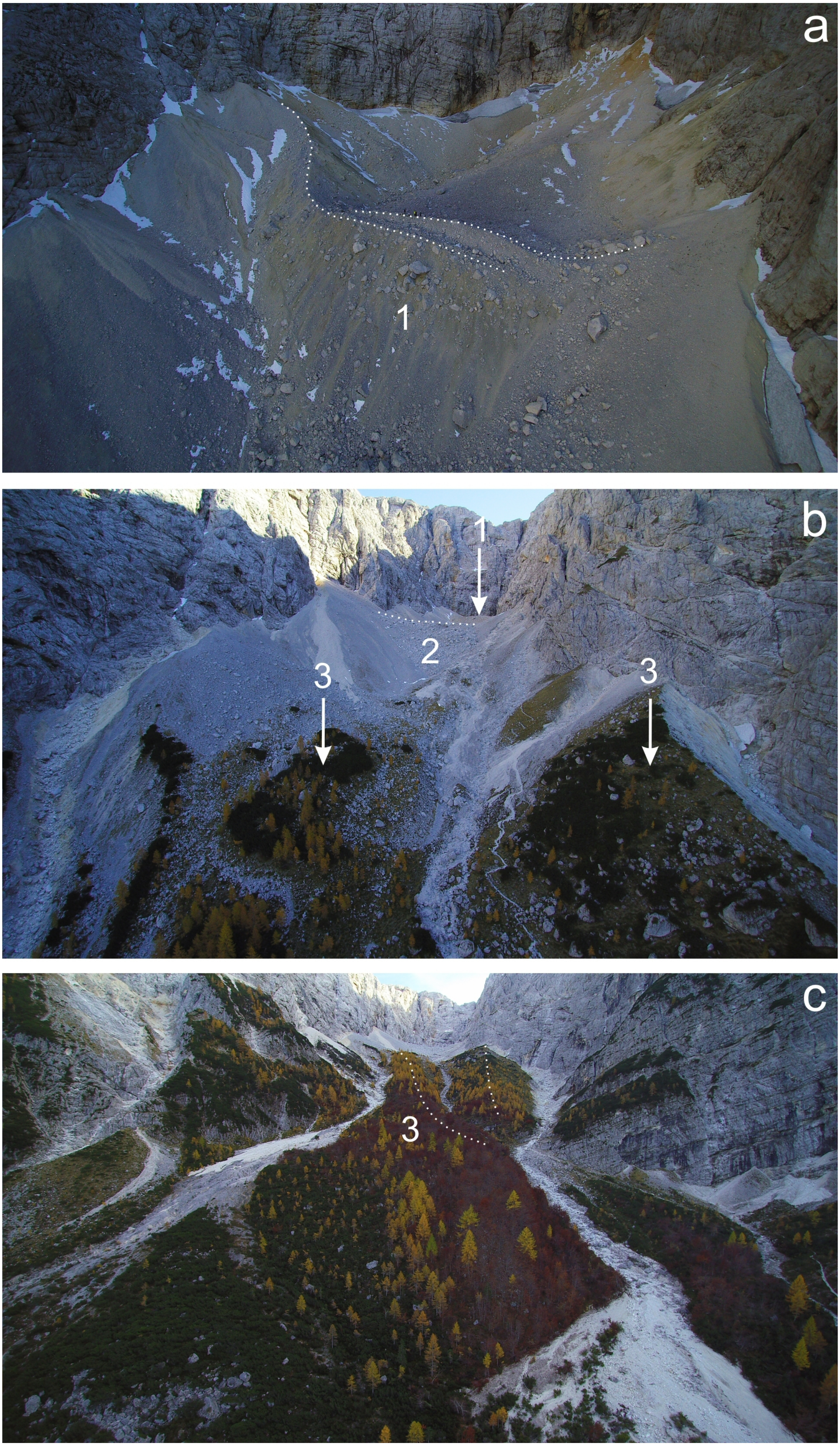


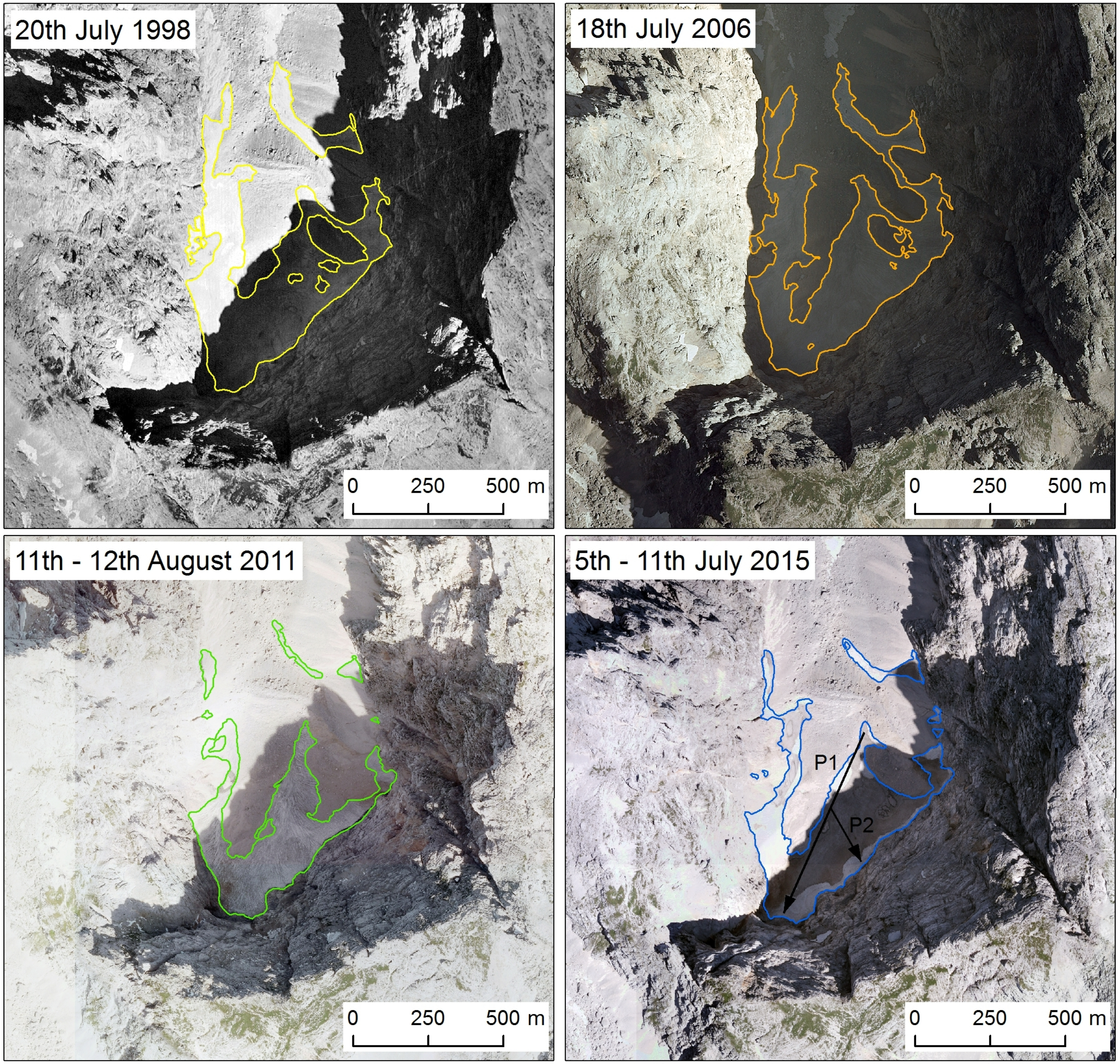
b
14°E
15°E
16°E
17°E
46°N
Krnica Valley
3
2
1
Sava
Julian Alps
Elevation (m asl)
2864
0
N
0 10 20 40 km
a
5°E
10°E
15°E
20°E
45°N
Alps
Adriatic Sea

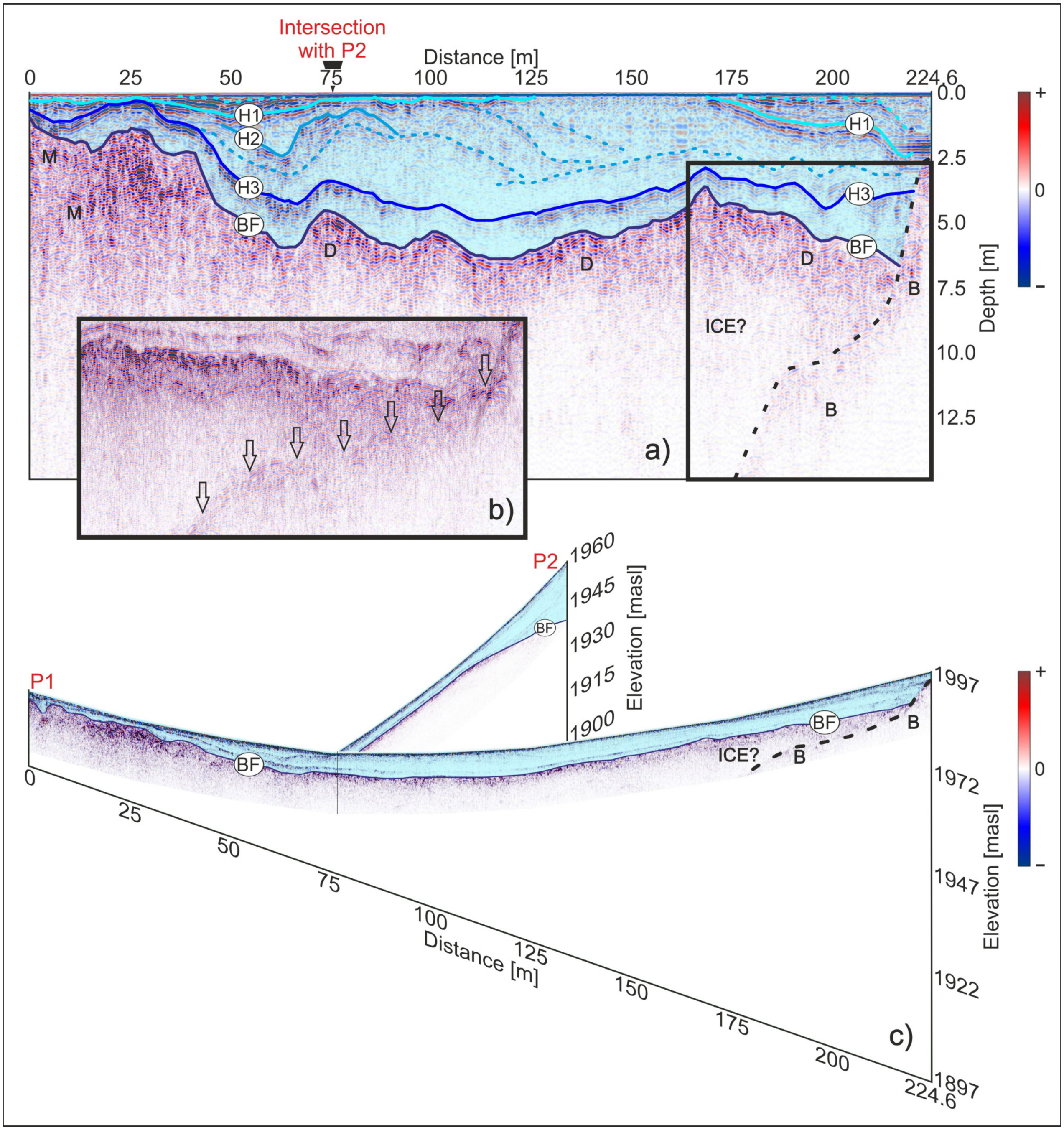

Frontal/lateral moraines
Rough glacier limit
LiDAR DEM
Flowline
Construct interval nodes: **25**
Nodes along the flowline
Define shear stress: **100 kPa - 200 kPa**
Nodes along the flowline with shear stress
Flowline ice thickness tool
Nodes with ice level and thickness
replace
Glacier surface interpolation: **Kriging**
DEM of palaeoglacier
ELA tool: AAR (MGE) and AABR (AA) for several ratios: **AAR ratios and interval: 0.2 - 0.8; 0.05**
Calculated ELAs
Automatic ice thickness recalculation with F factor
Cross-sections
Nodes with ice level recalculated with F factor (1)
F factor correction with user given cross-sections
Cross-sections
Nodes with ice level recalculated with F factor (2)



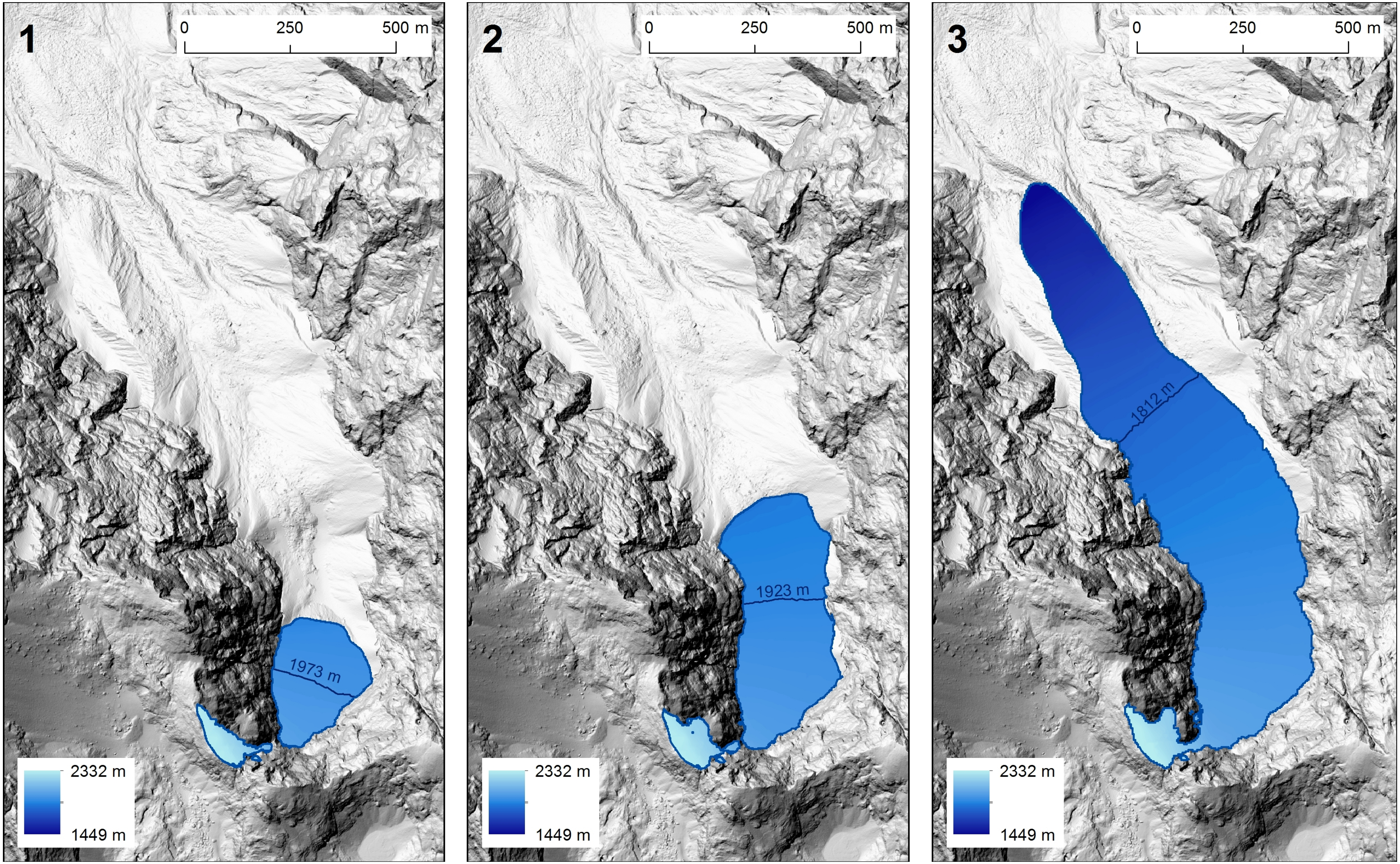
13°47'E
13°48'E
13°49'E
46°27'N
46°26'N
46°25'N
Mountain hut
Summit
Crest
Cirque crest
Moraine ridge
Covered moraine ridge
Main cone / fan
Perennial stream
Intermittent stream
Till
Stream dominated alluvial fan deposits
Gravity flow alluvial fan deposits
Debris flow-deposits
Avalanche deposits
Rockfall
Fluvio-torrential deposits
Snow patch in 2015
Bedrock
V. Pišnica
Krnica Mountain hut
Prisojnik 2547 m
Razor 2601 m
1
2
3
Figs. 7 and 9
Fig. 5
0
0.5
1 km


a
1
b
1
2
3
3
c
3

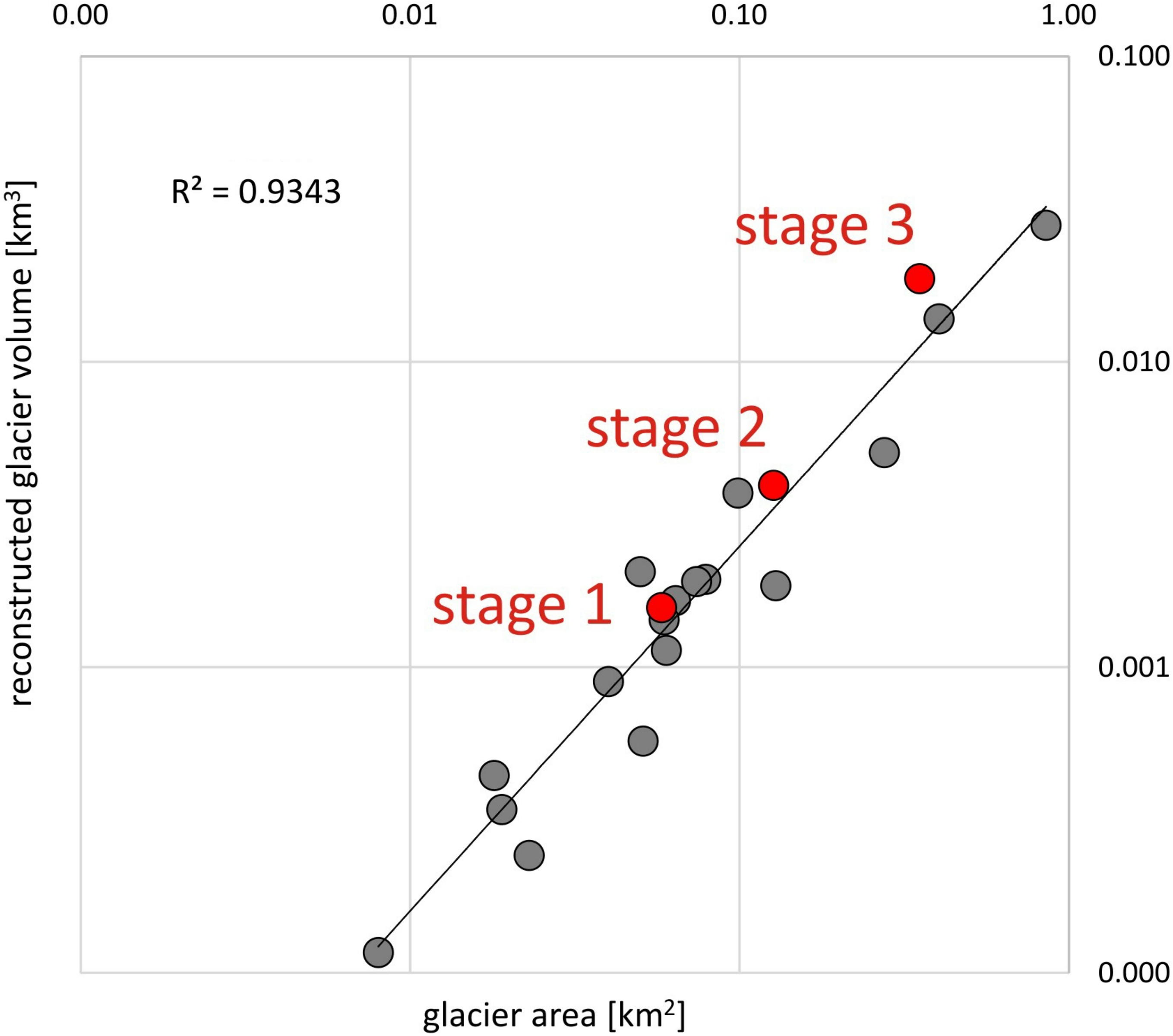

20th July 1998
0 250 500 m
18th July 2006
0 250 500 m
11th - 12th August 2011
0 250 500 m
5th - 11th July 2015
P1
P2
0 250 500 m

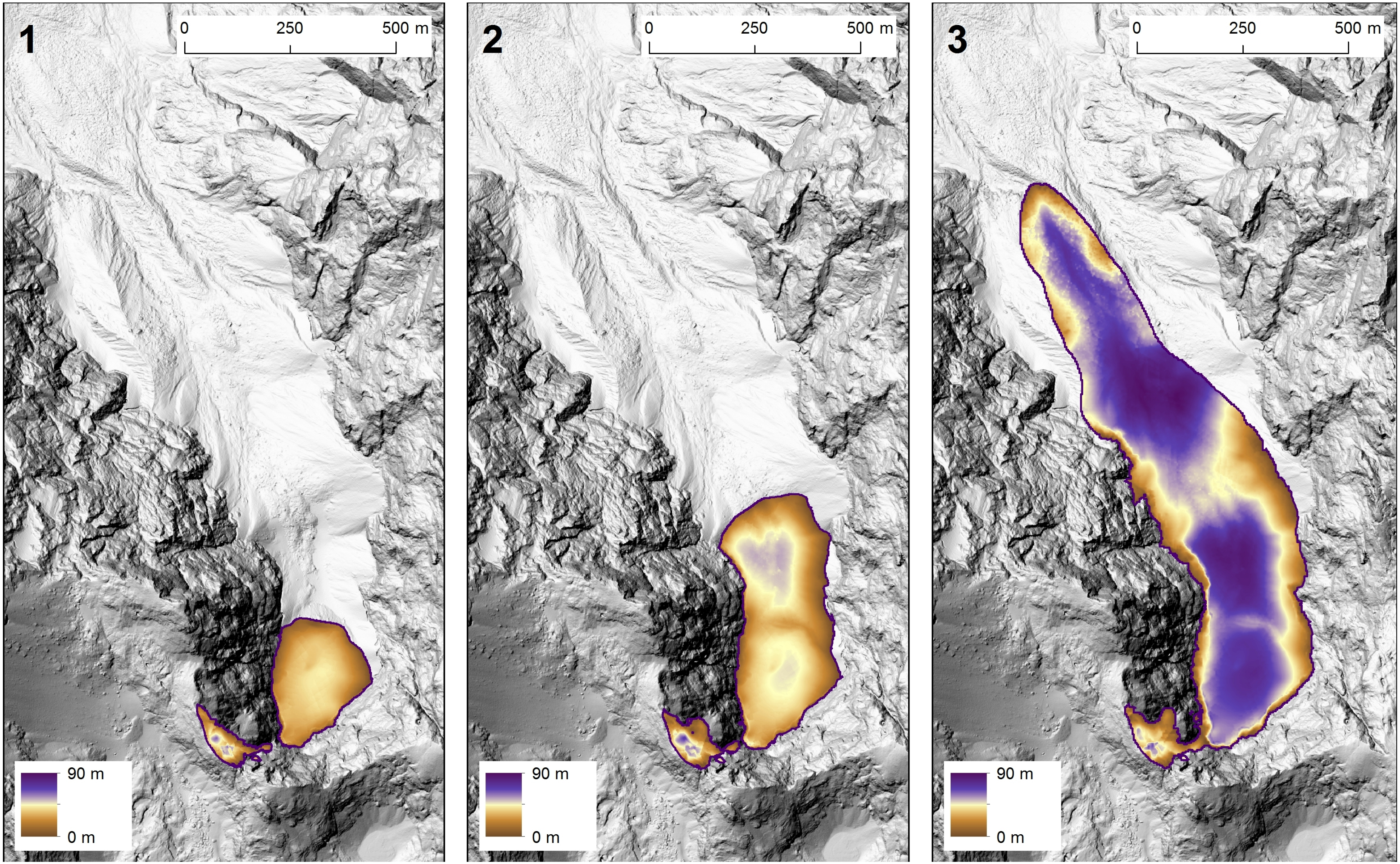


Intersection with P2
Distance [m]
0
25
50
75
100
125
150
175
200
224.6
0.0
2.5
5.0
7.5
10.0
12.5
Depth [m]
+
0
–
H1
H2
H3
BF
M
D
B
ICE?
a)
b)
P2
1960
1945
1930
1915
1900
Elevation [masl]
P1
1997
1972
1947
1922
1897
Elevation [masl]
Distance [m]
c)



1
0
250
500 m
1973 m
2332 m
1449 m
2
0
250
500 m
1923 m
2332 m
1449 m
3
0
250
500 m
1812 m
2332 m
1449 m


0.00
0.01
0.10
1.00
0.100
0.010
0.001
0.000
R² = 0.9343
stage 3
stage 2
stage 1
reconstructed glacier volume [km³]
glacier area [km²]


1
0
250
500 m
90 m
0 m
2
0
250
500 m
90 m
0 m
3
0
250
500 m
90 m
0 m