



# Glacial geomorphology of the Šumava / Bayerischer Wald mountains, Central Europe

David Krause and Martin Margold

Department of Physical Geography and Geoecology, Faculty of Science, Charles University, Prague, Czech Republic

## ABSTRACT

During Quaternary glacial periods, the Šumava / Bayerischer Wald mountains were subject to mountain glaciations. Recent studies have focussed mainly on the several well-developed cirques. However, the glacial geomorphology of the mountain range as a whole has not yet been mapped from digital data. Here we use high-resolution digital elevation models to identify over 300 erosional and 40 depositional landforms of glacial origin. Our study provides a map of glacial geomorphology for the whole mountain range across the Czech Republic, Germany, and Austria, with an up-to-date overview of previously investigated sites and newly identified glacial features in areas that have not previously been surveyed. The results of our mapping study can further be validated by field surveys and will serve as a basis for future reconstructions of palaeoglaciation in the Šumava / Bayerischer Wald mountains.

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Mountain glaciation; LiDAR DEM; Šumava; Bayerischer Wald; Central Europe; palaeoglaciation

## 1. Introduction

During the Quaternary, mid- and high-latitudes experienced glaciations both of mountain/alpine and ice sheet type (Ehlers, Gibbard, & Hughes, 2011). The data on the extents of glaciations are used by other disciplines, such as biology, anthropology, and palaeoclimatology. However, in many areas the extents, and also their timing, remain uncertain. The extents of glaciation are reconstructed through field surveying in combination with the use of remote sensing data; aerial photographs and digital elevation models (DEMs) are well-established types of data used for mapping the spatial distribution of glacial landforms (e.g. Chandler et al., 2018). The Light Detection and Ranging (LiDAR) technology has helped to significantly increase both the horizontal and the vertical resolution of DEMs over the last few years. Many countries have released detailed LiDAR DEMs recently, allowing detailed mapping of glacial landforms often in a higher detail than the mapping in the field could provide (e.g. Dowling, Spagnolo, & Möller, 2015; Hardt, Hebenstreit, Lüthgens, & Böse, 2015; Jónsson, Schomacker, Benediktsson, Ingólfsson, & Johnson, 2014; Ojala, Putkinen, Palmu, & Nenonen, 2015; Salcher, Hinsch, & Wagreich, 2010; Yu, Eyles, & Sookhan, 2015).

The Šumava / Bayerischer Wald mountains in Central Europe represent an example of a formerly glaciated area, where no complex mapping of glacial features has been done. The recent availability of LiDAR DEMs on the territory of the Czech Republic, Germany

and Austria presents a timely opportunity to carry out detailed geomorphological mapping focussed on glacial landforms in the area. The aim of this paper and the Main Map is to provide an overview of the spatial distribution of glacial features in the Šumava / Bayerischer Wald mountains. This is done by remapping previously investigated locations, filling the gaps in-between and providing a layer of digital data for future research concerned on the topic of past glaciations in the mountain range. Our mapping results can also serve as a basis for the development of conservation policy with respect to geomorphological heritage of the national parks in the area.

## 2. Study area

### 2.1. Geographical setting

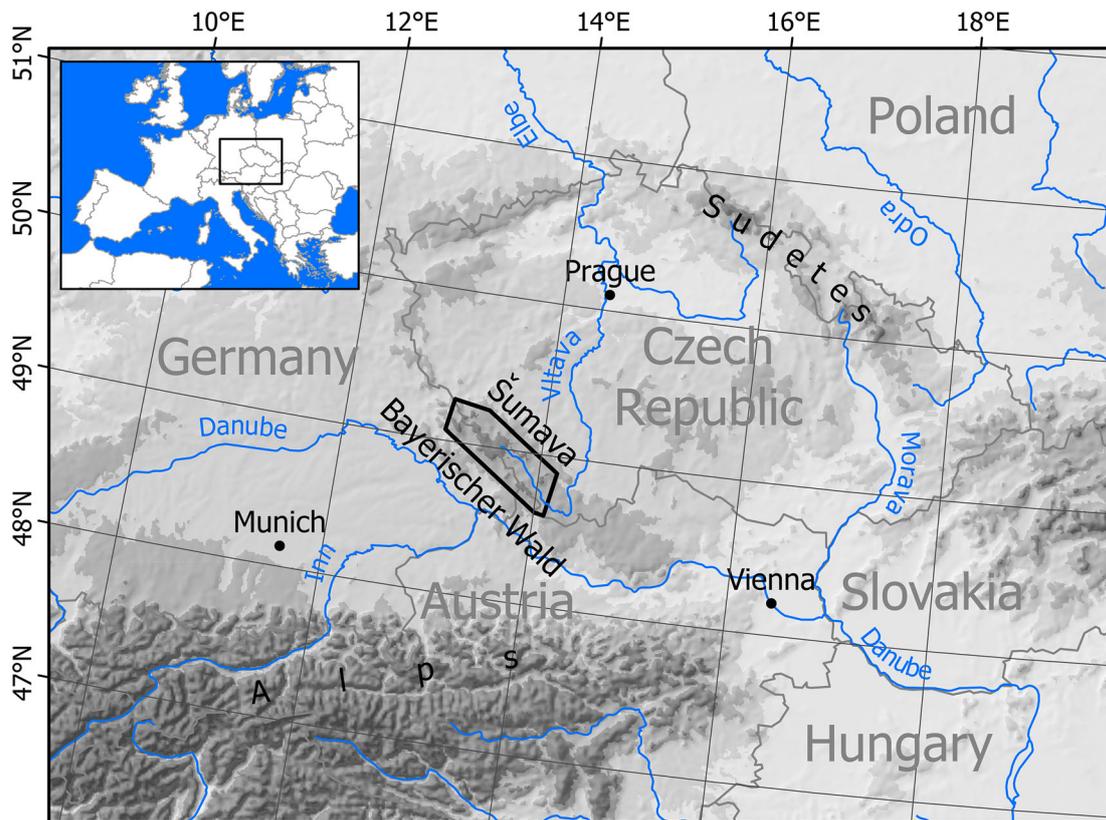
The Šumava / Bayerischer Wald mountains (also known as the Bohemian and Bavarian Forest in English or Böhmerwald and Bavorský les in German and Czech respectively) is a fault-block mountain range whose main axis forms the border between the Czech Republic and Germany, as well as the main water divide between the Northern and Black seas (Figure 1). The southeastern part of the mountain range belongs to Austria (Figure 1). The highest peak, Großer Arber, reaches to 1456 m above sea level (asl), while the central portion of the mountains is dominated by planation surfaces with relatively low relief and a large area with an elevation over 1000 m asl (over 350 km<sup>2</sup>). As

**CONTACT** David Krause david.krause@natur.cuni.cz Faculty of Science, Department of Physical Geography and Geoecology, Charles University, Prague, Czech Republic

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**Figure 1.** Location of the Šumava / Bayerischer Wald mountains. The extent of the Main Map is displayed by a black frame.

a part of the Bohemian Massif, the mountain range is composed of Variscan metamorphic and granitic rocks (Babůrek, Pertoldová, Verner, & Jiříčka, 2006) and its tectonic structure has been affected by the Alpine orogeny (Chlupáč, Brzobohatý, Kovanda, & Stráník, 2011). The natural heritage on both the Czech and German side of the border is protected by national parks: NP Šumava and NP Bayerischer Wald.

**Table 1.** List of the previously studied cirques in the Šumava / Bayerischer Wald mountains with references.

Name of the cirque	References
Kleiner Arbersee	Raab and Völkel (2003), Reuther et al. (2011)
Grosser Arbersee	Pfaffl (1988)
Schwarzer See (Černé jezero)	Vočadlova and Křížek (2009), Vočadlova et al. (2015)
Teufelsee (Čertovo jezero)	Vočadlova and Křížek (2009)
Lakka See (Jezero Laka)	Mentlík et al. (2013)
Stubenbacher See (Prášilské jezero)	Mentlík et al. (2010), Mentlík et al. (2013)
Mittagsbergkar (Stará jímka)	Mentlík et al. (2010), Mentlík et al. (2013), Procházka, Mizera, Kletetschka, and Vondrák (2019)
Hirschbachkar	Hauner (1980)
Kleines Rachelkar	Hauner (1980), Pfaffl (1988)
Grosses Rachelkar (Rachelsee)	Hauner (1980)
Bärenriegelkar (Shwarzbach)	Hauner (1980)
Pleckensteinsee (Plešné jezero)	Jankovská (2006)

Note: All the cirques have been described by Ergenzinger (1967) and his study also contains references to older literature on some of these cirques. Křížek et al. (2012) have studied the morphometric parameters of all the cirques listed. See the Main map for the location of the cirques.

## 2.2. Glacial geomorphology

During the cold stages of the Pleistocene, the Šumava / Bayerischer Wald mountains were one of several isolated mountain ranges subject to glaciation in the broad ice-free corridor between the Fennoscandian Ice Sheet in the north and the glaciated Alps in the south (Ehlers & Gibbard, 2004). The traces of past glaciation in the Šumava / Bayerischer Wald were first described in the nineteenth century (Bayberger, 1886) and have been studied ever since (e.g. Ergenzinger, 1967; Hauner, 1980; Křížek, Vočadlova, & Engel, 2012; Mentlík, Engel, Braucher, Léanni, & Team, 2013; Preihäusser, 1934; Raab & Völkel, 2003; Rathsburg, 1927; Reuther et al., 2011; Vočadlova et al., 2015; Votýpka, 1979). Most of the studies, especially the most recent, have focussed mainly on some of the twelve identified cirques (Table 1) or short valley-glacier locations with well-preserved glacial landforms, and dated these to the Würm period – Marine Isotope Stage (MIS) 2 (Mentlík et al., 2013; Raab & Völkel, 2003; Reuther et al., 2011; Vočadlova et al., 2015). Calculated equilibrium line altitudes (ELAs) from the cirque locations are ranging from 925 to 1145 m asl (Mentlík et al., 2013; Raab & Völkel, 2003), which is well below the elevation of the central summit areas (usually over 1200 m asl). In addition, there have been moraines described in lower elevations (670–890 m asl) in the valleys on the southwestern slopes of the mountains (Ergenzinger, 1967; Hauner, 1980).

Based on these moraines, a hypothesis of a more extensive glaciation was proposed and described in detail by Ergenzinger (1967), who presented a map of glacial landforms and reconstructed an ice field based on an ELA of 1060 m asl derived from the mapped landforms. The map of Ergenzinger consists of field evidence from the German part of the mountain range exclusively and the extent of glaciation was extrapolated to the Czech territory using topographic maps. The total area of suggested ‘maximum Würm’ glacial extent is 646 km<sup>2</sup> (Ergenzinger, 1967). Climatic degree-day modelling performed by Heyman, Heyman, Fickert, and Harbor (2013) yielded a similar extent of glacial accumulation area for conditions with 10.7 °C lower mean annual temperatures (MAATs) than at present. More research is needed to reconstruct the glacial history of the mountain range, both in terms of the extents of the past glaciation and their chronology.

The glacial history of the Šumava / Bayerischer Wald mountains ties to the glacial history of the Eastern Alps located only about a hundred kilometres to the south across the Danube valley (Figure 1). The extents and chronologies of the originally established glacial stratigraphy (Würm, Riss, Mindel, respectively, for the last, penultimate and antepenultimate glaciation; Penck, 1882; Penck & Brückner, 1901/1909) are being refined (Bickel, Lüthgens, Lomax, & Fiebig, 2015; Fiebig, Ellwanger, & Doppler, 2011; Preusser, Graf, Keller, Krays, & Schlüchter, 2011; Salcher, Starnberger, & Götz, 2015; Van Husen & Reitner, 2011). This presents the opportunity to study the glacial history of the Šumava / Bayerischer Wald mountains in more detail and compare the glacial histories against one another.

### 3. Data and methods

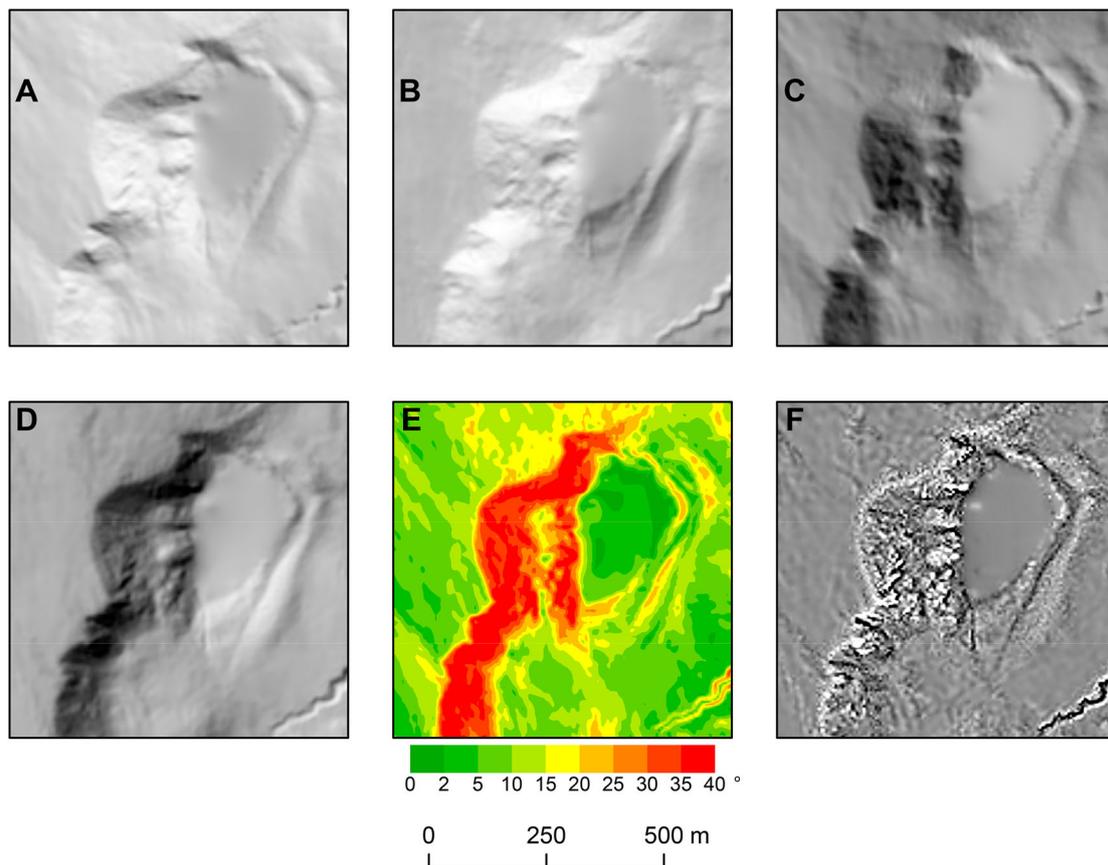
#### 3.1. Data collection and mapping methodology

The Šumava / Bayerischer Wald mountains stretch across three countries: Germany, the Czech Republic, and Austria; different DEMs or DEM-derived imagery were therefore used for each of the countries. For the Czech part of the study area, the Digital Terrain Model of the Czech Republic of the 4th generation (‘DMR 4G’) was obtained from the State Administration of Land Surveying and Cadastre. These elevation data are a part of the ZABAGED Geodatabase containing detailed spatial data of the country in the scale of 1:10,000. The LiDAR-based elevation model is provided in 5 × 5 m grid with vertical random error of approximately 30 cm. On the territory of Austria, the Digital Terrain Model of Austria of 10 m resolution was used. The data were downloaded from the Land Upper Austria online portal as a 10 × 10 m grid. For the German part of the mountains we only had a

hillshade image available derived from the DGM1 product produced by the Bavarian State Office for Digitization, Broadband and Surveying. The spatial resolution of the hillshade image was 1 m. In each country, the data have been analysed separately.

Multiple raster images for surface GIS (geographical information systems) analysis were generated from the DEMs for the Czech Republic and Austria, keeping the original spatial resolution of the DEMs. The following types of derived raster images were employed for the detection of glacial features: (1) *Hillshaded relief*, where the shades display breaks of slope that delineate the edges of landforms. To avoid bias arising from using illumination from one direction only (Smith & Clark, 2005; Smith & Wise, 2007), we used four directions of illumination: 45°, 135°, 245°, and 315°. The height of the illumination source was 45° in all cases (Figure 2). The final raster images were visualised using two different range distributions: histogram-equalised, to increase the shade intensity for detecting landforms with lower relief (e.g. remnants of moraines, indistinct glacial cliffs), and minimum-maximum, to lower the contrast and let sharp glacial features stand out (e.g. pronounced glacial cliffs). For the German part of the mountains, only a hillshade with 315° direction and 45° source height was used (as we did not have the original DEM available). (2) *Slope gradient*, which helps to visualise the shape of landforms and to identify escarpments. Based on the study area relief, the raster was classified into the following classes: 0–2°, 2–5°, 5–10°, 10–15°, 15–20°, 20–25°, 25–30°, 30–35°, and more than 35°. (3) *Contours*. We used contours with 10 m vertical interval as an accessory for raster analysis. (4) *Curvature*. Combined plan and slope curvature was used as an accessory raster for verifying the mapped edges of landforms.

Glacial landforms in the study area were manually delineated in the above-described GIS data and classified into two main groups: (a) *glacial erosion features*, and (b) *glacial depositional features*. The *glacial erosion features* group contains *glacially formed cliffs* in three levels (Figure 3): *well developed* (clearly visible features with certain glacial origin), *poorly developed* (visible features with highly probable glacial origin) and *speculative* (features of possible glacial origin). The *glacial depositional features* group contains *well developed-* and *poorly developed moraines* as well as other *potential glacigenic accumulations* and *sandurs* (Figure 3). All these landforms were mapped using remote sensing data only and their origin was not verified by geomorphological and sedimentological field surveys. Hence, only clearly visible landforms showing morphologically distinct or highly probable glacial origin were mapped. In most cases, these landforms show visual similarity to the forms described in the cirque locations (Tab. 1).



**Figure 2.** Examples of DEM-derived images used for the mapping: hillshaded relief with illumination direction 45° (A), 135° (B), 245° (C) and 315° (D); slope gradient in degrees (E); curvature, black: concave parts of the surface, white: convex parts of the surface (F). For the location of the area, see [Figure 3](#).

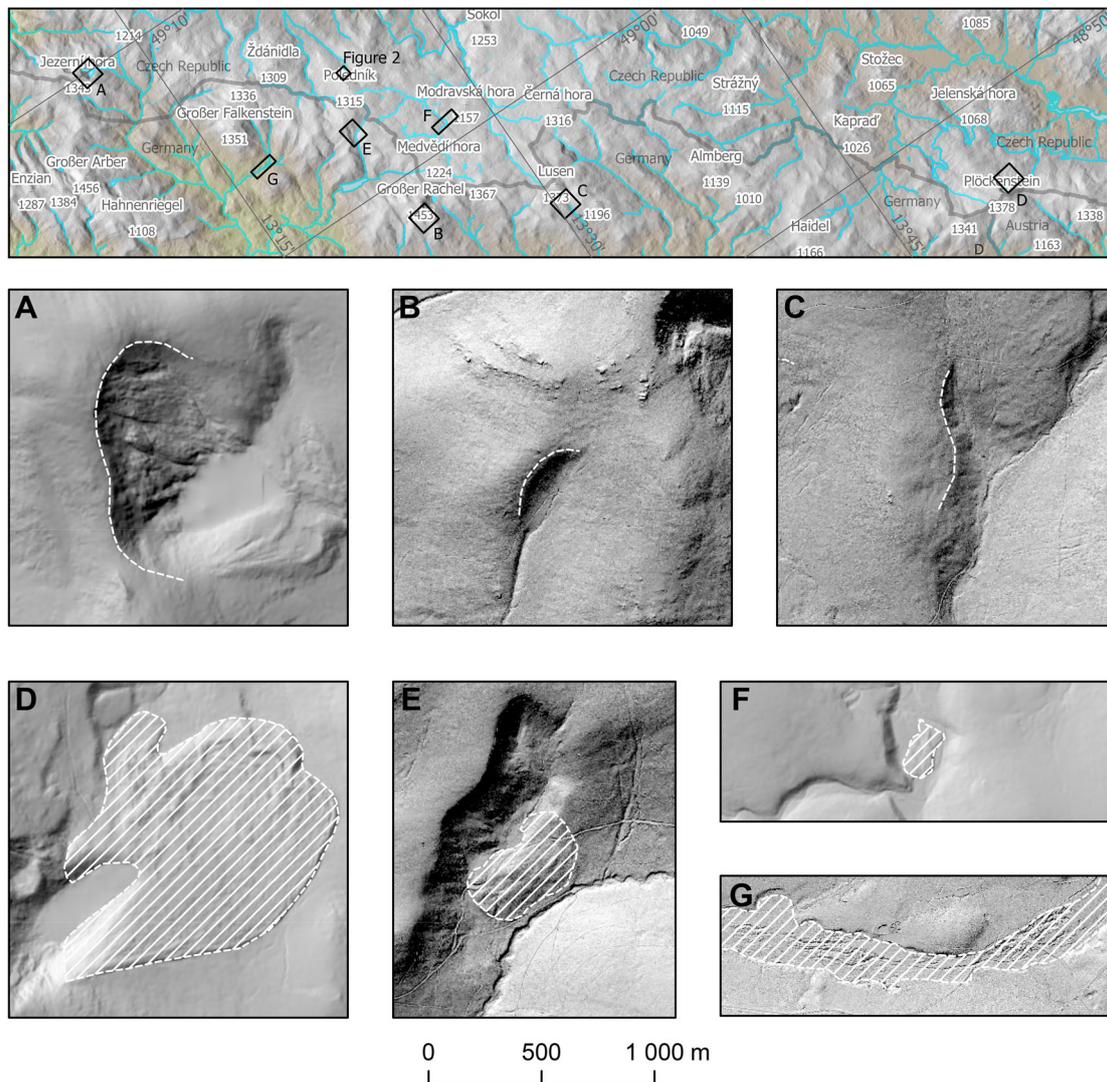
### 3.2. Map creation

The Main Map is designed as a wall map in dimensions of A0 landscape format (841 × 1189 mm), with the main map panel displaying the mapped glacial landforms of the Šumava / Bayerischer Wald mountains. The main map panel is at the scale of 1:75,000 and has elevation data displayed by contours with an interval of 50 m complemented by a semi-transparent hillshade (illumination azimuth 315°, altitude 45°). Hydrographic features, summit points, and populated places are added to the map for easier orientation of the map reader. The primary content of the map (i.e. the glacial features) is depicted using distinct symbology, which is explained in the Legend. The glacial extent suggested by [Ergenzinger \(1967\)](#) is displayed as well. Ten additional maps at the scale of 1:25,000 showing thirteen best-developed glacial cirques complement the main map panel in order to display the mapped glacial features at a larger scale. The background of these maps is represented by hillshade images with 315° azimuth and 45° altitude of illumination and 10 m grid. These images have been derived from the original DEMs described in Section 3.1. Geological map depicting the lithology of the mountain range at the scale of 1:300,000 is also added to the map layout. The geological map was created by

generalisation of three different national geological maps: Bavarian State Office of Geology (1996): Geological map 1:500,000, Geological Survey of Austria (2019): Geological map 1:1,000,000 and Czech Geological Survey (2007): Geological map 1:500,000. Locations of the map frames of the best-developed glacial cirques and the state borders are printed in the geological map for better orientation of the reader.

### 4. Mapping results, implications and conclusions

Geomorphological mapping from detailed DEMs allowed us to produce a map of glacial landforms for the whole Šumava / Bayerischer Wald mountains (see the Main Map). We remapped previously described glacial landforms ([Tab. 1](#)) but we also present a number of newly identified glacial features in the area. Some of the newly identified features are clearly of glacial origin while for others the glacial origin is more speculative. In total, we mapped over 300 erosional and over 40 depositional landforms. The most abundant feature is a glacial cliff, in contrast to the lack of glacial depositional landforms. The mapped glacial cliffs are facing to the east in most cases. The majority of mapped features (almost all in the German part of



**Figure 3.** Examples of glacial landforms mapped in this study: well developed (A), poorly developed (B) and speculative (C) glacial cliff; well developed (D), poorly developed (E) moraine; potential glacial accumulation (F); sandur (G). Locations of these examples and the example shown in Figure 2 are shown in the inset map.

the mountains) are located within the ‘maximum Würm’ extent of glaciation as suggested by Ergenzinger (1967), except for the relict sandurs. Glacial erosion features outside of the glacier extent of Ergenzinger are found in the western part of the mountains, in the westernmost area north of Ostrý Mt. (1293 m asl), and east of Můstek (1235 m asl) and Pancíř (1214 m asl), and mountains around the peak of Javorná (1090 m asl; see the Main Map). The density of glacial features decreases to the east. Ergenzinger (1967) suggestion of glaciers on Boubín (1362 m asl) and Bobík (1264 m asl) mountains, Almborg Mt. (1139 m asl), Grandelberg Mt. (1010 m asl), Haidel Mt. (1166 m asl), Knížecí stolec Mt. (1226 m asl), Špičák Mt. (1221 m asl) and Chlum Mt. (1192 m asl) are not supported by glacial landforms mapped in this study.

The distribution and morphology of the mapped features is consistent with the suggested climatic conditions at the time of their origin (Barr & Spagnolo, 2015). The cirques and proto-cirques with different degree of development ranging from classic to

marginal (sensu Evans & Cox, 1995) are mainly facing to the east, which probably reflects the western winds of the glacial periods (Meyer & Kottmeier, 1989; Renssen, Kasse, Vandenberghe, & Lorenz, 2007) redistributing snow into leeward positions (Jeník, 1961). The absence of mapped features in the eastern part of the mountains can be explained by lower accumulation rates in the precipitation-shadow of the mountains. The accumulation rates were either too low to sustain the growth of glaciers in the precipitation-starved parts of the mountains or glaciers were cold-based and left no erosional traces of their existence.

Using the Last Glacial Maximum (LGM) temperatures from the available palaeoclimatic studies for the region (Allen, Siebert, & Payne, 2008; Ramstein et al., 2007), Heyman et al. (2013) modelled ice extents similar to the reconstruction of Ergenzinger (1967). Results of our mapping are consistent with this, identifying a number of glacial features located predominantly in the area suggested to have been glaciated (Ergenzinger, 1967; Heyman et al., 2013). The timing and extent of

the more extensive glaciation remain unclear and need to be studied further. Thus, our remote-sensing mapping survey should serve as a basis for future field-based and numerical modelling research.

The glacial geomorphology of the Šumava / Bayerischer Wald mountains is best expressed in the form of classic glacial cirques but the glacial imprint containing erosional and depositional landforms extends over most of the mountain range and indicates a relatively extensive glaciation at some point in the past.

## Software

Mapping of glacial features and the DEM analyses were carried out in ArcMap 10.3 (ESRI, 2014). The final layout of the map set was produced in ArcGIS Pro (ESRI, 2017).

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## Disclosure statement

No potential conflict of interest was reported by the authors.

## ORCID

David Krause  <http://orcid.org/0000-0001-5224-8954>  
Martin Margold  <http://orcid.org/0000-0001-5834-850X>

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