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Patterned ground above the alpine timberline in the High Sudetes, Central Europe

Marek Křížek [a], David Krause [a,b], Tomáš Uxa [a,c], Zbyněk Engel [a], Václav Treml [a] and Andrzej Traczyk [d]

[a]Department of Physical Geography and Geoecology, Faculty of Science, Charles University, Praha, Czech Republic; [b]The Krkonoše Mountains National Park Administration, Vrchlabí, Czech Republic; [c]Department of Geothermics, Institute of Geophysics, Academy of Sciences of the Czech Republic, Praha, Czech Republic; [d]Department of Geomorphology, Faculty of Earth Sciences and Environmental Management, University of Wrocław, Wrocław, Poland

ABSTRACT
Patterned ground in mountainous areas has a high palaeogeographic significance as it is associated with cold environments and frequently with permafrost conditions. Most patterned ground (i.e. sorted polygons, sorted nets, sorted stripes) in the High Sudetes is overgrown by vegetation and is relict. However, wind-blown summit areas with low snow cover allow for the activity of sorted circles, earth and peat hummocks, and some non-sorted stripes. The extent of patterned ground above the alpine timberline in the High Sudetes presented here is based on detailed field geomorphologic mapping. Patterned ground occurs on summit planation surfaces and surrounding gently sloping terrain, and covers 5.23 km^2. Sorted polygons are the highest-elevated patterned-ground type. The spatial distribution of patterned ground is shown in the map, which could be helpful for future research of the Quaternary geomorphologic evolution of the mountain landscape and for nature protection planning in the High Sudetes.

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Patterned ground; sorted polygons; earth hummocks; High Sudetes; Central Europe

1. Introduction

The term patterned ground refers to a wide group of periglacial landforms showing more or less regular surface geometric patterning in the form of circles, polygons, irregular nets or stripes (e.g. Ballantyne, 2018; French, 2017; Warburton, 2013; Washburn, 1979). Depending on the presence or absence of particle sorting, patterned ground is genetically divided into sorted and non-sorted varieties (Washburn, 1956). Sorted patterned ground consists of fine-grained cells bordered by mostly vertically-oriented coarser clasts. Sorted polygons or nets occur on flat or gently sloping ground (3–6°), but tend to elongate downslope due to solifluction, and on steeper slopes (more than 4–11°) they evolve into sorted stripes or steps (Goldthwait, 1976). Small-scale sorted patterns usually form within the seasonally frozen ground (Haugland, 2004; Matthews, Shakesby, Berrisford, & McEwen, 1998), but large sorted polygons and nets are considered to be associated with the permafrost environment (French, 2017). Non-sorted patterned ground is defined by microrelief and/or vegetation cover (Ballantyne, 2018; French, 2017; Washburn, 1979). Semi-circular, dome-shaped (hummocky) non-sorted patterned ground arising on flat surfaces or gentle slopes is commonly named as earth or peat hummocks (e.g. Grab, 2005; Treml, Křížek, & Engel, 2010; Van Vliet-Lanoë & Seppälä, 2002). Likewise, earth hummocks turn to non-sorted stripes as a result of solifluction on steeper slopes (Washburn, 1979). These stripes are sometimes termed hummock stripes or relief stripes (Ballantyne, 2018). Non-sorted patterned ground also frequently forms within the permafrost active layer, but analogously to small-scale sorted patterned ground, they may form in the seasonally frozen ground as well (Ballantyne, 1996; French, 2017).

Different patterned-ground types require distinct climate conditions, and this is reflected in their spatial and altitudinal distribution (Harris, 1982; Jahn, 1979; Niessen, Van Horssen, & Koster, 1992; Washburn, 1970) and morphology (Křížek & Uxa, 2013; Uxa, Mida, & Křížek, 2017), but they could be modified by lithology, grain size distribution, depth of groundwater table, or slope angle etc. Thus, the relict patterned ground can be used to reconstruct permafrost and climate history of the region, especially in summit areas of mountains, where other palaeoclimate indicators do not occur. Different morphology of patterned-ground types can be used as a distinguishing factor for their classification. Thus, the field mapping of different types of patterned ground is an important issue regarding both validation

CONTACT David Krause david.krause@natur.cuni.cz
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data for an automatic classification of these periglacial phenomena (Hjort & Luoto, 2006) and palaeoenvironmental reconstruction models.

The main aim of the paper is to present the first cross-border overview map of patterned ground above the alpine timberline in the whole High Sudetes, Central Europe, based on field geomorphological mapping.

2. Study area and patterned ground in the High Sudetes

The High Sudetes, along the border of the Czech Republic and Poland, consist of three isolated mountain ranges (Main map; Front page): the Krkonoše Mts. (the Giant Mts. or the Karkonosze Mts. or Riesengebirge) on the west and the Králický Sněžník Mts. (the Masyw Śnieżnika Mts. or Glatzer Schneegebirge) and the Hrubý Jeseník Mts. (the Wysoki Jesionik Mts. or Altvatergebirge) on the east. Their highest peaks are Mt. Sněžka (1603 m asl) in the Krkonoše Mts., Mt. Praděd (1491 m asl) in the Hrubý Jeseník Mts. and Mt. Králický Sněžník (1424 m asl). The High Sudetes are Variscan fault-block ranges with deep valleys, steep slopes affecting current debris flow (Gába, 1992; Křížek, Krause, & Raschová, 2018; Pilous, 1973) and avalanche (Kociánová, Kořízek, Spusta, & Brzeziński, 2013; Krause & Křížek, 2018) activity, and summit plateaus at elevations of 1300–1555 m asl, which rise above the alpine timberline (Treml & Migoń, 2015). The western part of the High Sudetes is mainly built of metamorphic (gneiss, mica schist, phyllite, and quartzite) and plutonic rocks (granite), while the eastern part of the High Sudetes is dominated by metamorphic rocks (gneiss, mica schist, phyllite, quartzite, and calc-silicate hornfel) (Chlupáč, Brzobohatý, Kovanda, & Stráník, 2011). The summit planation surfaces, as a result of long-term denudation and remnant of peneplain, probably started to form around 75 Ma (Danišík et al., 2010) and differentially uplifted in the Neogene and Quaternary. The total Cenozoic uplift is estimated at up to 1200 m (Kopecký, 1986).

The High Sudetes were 120 km (for the Krkonoše Mts.) to 180 km (for the Hrubý Jeseník Mts. and Králický Sněžník Mts.) south of the Scandinavian ice sheet during the last Pleistocene glaciation, and thus most of their area was affected by periglacial conditions (Czudek, 2005). The summit planation surfaces were very important for the formation of glacial and periglacial landforms in the Quaternary. Snow was largely blown from the summit planation surfaces and deposited in the leeward parts of valleys where about 15 (i.e. some cirque locations are still under debate) mostly cirque glaciers and up to 5 km long valley glaciers developed in the last glacial period (MIS 2) (Engel, Braucher, Traczyk, & Laetitia, 2014; Králík & Sekyra, 1969; Křížek, Vočadlová, & Engel, 2012). The equilibrium line altitude occurred at 1060 m asl on the western part of the High Sudetes (Křížek et al., 2012), while it was at 1170 m asl on the eastern part of the High Sudetes (Křížek, 2016). On the other hand, thin snow cover on the wind-exposed summit plateaus enabled deeper ground freezing and more intensive freeze–thaw cycles, frost weathering and sorting (Křížek & Uxa, 2013; Sekyra, 1960), which led to the origin and development of sorted polygons, nets and stripes (Klementowski, 1998; Křížek, 2016; Kunský & Záruba, 1950; Prosová, 1952; Traczyk, 1996; Treml et al., 2010) during the last glacial period (Sekyra et al., 2002; Sekyra & Sekyra, 1995; Traczyk & Migoń, 2000) in the permafrost conditions (Czudek, 2005). These above-mentioned large-scale sorted polygons, nets and stripes have not been active during the Holocene (Treml et al., 2010) and most of them are currently partly or fully overgrown by graminoids. The secondary sorting centres of sorted polygons and nets, as an evidence of their possible reactivation, were observed only at the top of Mt. Luční hora, but the reactivation did not lead to any significant changes in the overall structure of sorted polygons and the secondary sorting centres are an order of magnitude smaller than the respective sorted polygons, and thus it was of marginal importance (Křížek & Uxa, 2013). However, current climatic conditions in the summit deflation areas with low snow cover allow the activity of sorted circles, earth hummocks, peat hummocks, and some non-sorted stripes (Kociánová, Štursová, Váňa, & Jankovská, 2005; Křížek, 2016; Křížek, Treml, & Engel, 2010; Prosová, 1958; Sekyra & Sekyra, 1995; Treml et al., 2010). The current mean annual air temperature in the highest parts of the High Sudetes is from 0 to +2°C (Mt. Sněžka 1881–2010: +0.5°C; Migała, Urban, & Tomczyński, 2016; Mt. Praděd 1960–1990: +1.7°C; Coufal, Míková, & Langová, 1992) and mean annual precipitation increases with altitude about 1500 mm (Jeník & Sekyra, 1995), but there is no credible evidence of near-surface permafrost occurrence in the patterned-ground areas in the High Sudetes (Křížek, 2016; Uxa et al., 2019). The study area is situated in above the alpine timberline defined by Treml and Migoń (2015), and its area is 45.78 km^2 (the Krkonoše Mts. 38.73 km^2, the Králický Sněžník Mts. 0.78 km^2, the Hrubý Jeseník Mts. 6.27 km^2). The average elevation of the alpine timberline is located at ca 1250 m asl in the Krkonoše Mts., but in the Hrubý Jeseník Mts. and the Králický Sněžník Mts. it is above 1300 m asl because of their greater continentality (Treml & Migoń, 2015). This alpine timberline ecotone naturally lacked dwarf pine (*Pinus mugo*), which is a native species in the Krkonoše Mts. and a non-native species in the Hrubý Jeseník Mts. (Rybníček & Rybníčková, 2004). However, dwarf pine was planted near the alpine timberline in the second half of the nineteenth century, and today covers large areas above it and has gradually covered part of patterned-ground areas (Treml & Křížek, 2006).

3. Methods

3.1. Data collection

The extent of patterned ground is based on detailed field geomorphological mapping of the forest-free area above the alpine timberline in the whole High Sudetes. Each patterned-ground area was delineated by hand-held GPS device (horizontal accuracy of ±3 m) and classified into one of the following patterned-ground categories: (1) sorted polygons, (2) sorted nets, (3) sorted circles, (4) sorted stripes, (5) earth hummocks, (6) peat hummocks, and (7) non-sorted stripes (Figure 1). Trenching was used in selected localities to check the inner structure of the patterned ground and to distinguish between the sorted and non-sorted patterns. Additionally, aerial photos from 2006, 2009–2010, 2014–2015, 2017 (GEODIS and TopGis) and orthorectified aerial photographs from the year 2016 (the Czech State Administration of Land Surveying and Cadastre) supported the field

Figure 1. Examples of patterned ground in the High Sudetes. 1 – sorted polygons at Mt. Břidličná, the Hrubý Jeseník Mts.; 2 – sorted nets at the Modré sedlo Saddle, the Krkonoše Mts.; 3 – sorted circle at the Modré sedlo Saddle, the Krkonoše Mts.; 4 – sorted stripes on southern slope of Mt. Luční hora, the Krkonoše Mts.; 5 – profile through the earth hummock at Mt. Praděd, the Hrubý Jeseník Mts.; 6 – peat hummocks on the Bílá louka Meadow, the Krkonoše Mts.; 7 – non-sorted stripes on the Bílá louka Meadow, the Krkonoše Mts.

mapping and helped refine the patterned-ground boundaries. The default digital elevation model (DEM) of 1 × 1 m grid and 0.1–0.2 m vertical resolution was derived from the light detection and ranging (LiDAR) point clouds provided by the Czech State Administration of Land Surveying and Cadastre and the Polish Head Office for Geodesy and Cartography. The LiDAR-based DEM was used to derive the raster images such as hillshade, aspect and slope, which also helped to delineate the boundaries of patterned-ground areas in detail.

Morphometric parameters of each patterned-ground type were computed from the above-mentioned DEM. The basic statistics of elevation, slope angle and aspect were based on all raster cells intersecting the areas of each patterned-ground type in the three studied parts of the High Sudetes.

3.2. Map creation

The mapping results are presented in five separate maps on three pages of A1 landscape format. Each of these maps covers one separated area above the alpine timberline in the High Sudetes: the western and eastern part of the Krkonoše Mts., the Králický Sněžník Mts., and the southern and northern part of the Hrubý Jeseník Mts. The scale of all these maps is 1:14,000 and the projected coordinate system is S-JTSK – Krovak East-North (EPSG 5514). The background maps contain the DEM-derived hillshade image (standard illumination azimuth 315°, altitude 45°) and contour lines with an interval of 50 vertical metres. The names and elevations of main mountain peaks are printed. Basic topographic map colour scheme was used in the background maps (*sensu* Kraak & Ormeling, 2013). The patterned-ground areas, as the main content of the maps, are visualized in colour hatch according to each of the seven patterned-ground categories to be easily readable and distinguishable: the sorted patterns in the black hatch and the non-sorted patterns in the brown hatch. Moreover, each patterned-ground category has a unique colour to support the map legibility: (1) light yellow for sorted polygons, (2) light blue for sorted nets, (3) pink for sorted circles, (4) light green for sorted stripes, (5) light salmon for earth hummocks, (6) light beige for peat hummocks, and (7) light ocher for non-sorted stripes.

4. Mapping results and conclusions

Patterned ground of the High Sudetes comprises sorted (i.e. sorted polygons, sorted nets, sorted stripes, sorted circles) and non-sorted (earth hummocks, peat hummocks and non-sorted stripes) variety (Figure 1). The total area of patterned ground is 5.23 km^2, which represents ca 11.4% of the area above the alpine timberline in the High Sudetes. The largest areas cover sorted nets and sorted stripes, ca 2.96 km^2 (57% of the total patterned-ground area) and ca 1.86 km^2 (36% of the total patterned-ground area), respectively (Table 1). On the contrary, sorted circles cover less than 450 m^2 (0.009% of the total patterned-ground area).

Sorted circles (0.7–1.4 m in diameter) occur exclusively on flat to gently sloping surfaces (Figure 2) at the Modré sedlo Saddle (1510 m asl) and Mt. Luční hora (1555 m asl) in the Krkonoše Mts. Their initial forms (about 0.2 m in diameter) also emerge occasionally at a very limited spot at the wind-exposed top of Mt. Keprník (1423 m asl) in the Hrubý Jeseník Mts., but these small-scale sorted circles are usually trampled and damaged by tourists.

Sorted polygons (length: 1.6–10.5 m; width: 1.4–6.0 m; height: 0–0.45 m) developed mostly on gentle slopes (2–4°, Figure 2) and they are the highest-elevated patterned-ground type in the High Sudetes. More than 90% of these landforms occur in the Krkonoše Mts. (Main map; page 1, 2) between 1483 and 1551 m asl (Figure 3). In the Králický Sněžník Mts. and the Hrubý Jeseník Mts. (Main map; page 3), they occur at lower altitudes (from 1355 to 1419 m asl) because of the lower altitude of these mountain ranges in general.

Most sorted nets (length: 1.0–6.1 m; width: 0.8–4.8 m; height: 0.1–0.7 m) occur on flat surfaces to gentle slopes (1–3°, Figure 2) at altitudes from 1382 to 1462 m asl, which show no substantial variations across the High Sudetes (Figure 3). Sorted polygons and nets

Table 1. Patterned-ground types in the High Sudetes and their extents.

	High Sudetes		Krkonoše Mts.		Králický Sněžník Mts.		Hrubý Jeseník Mts.	
Patterned-ground category	Area (km^2)	Percentage	Area (km^2)	Percentage of total patterned-ground area in the High Sudetes	Area (km^2)	Percentage of total patterned-ground area in the High Sudetes	Area (km^2)	Percentage of total patterned-ground area in the High Sudetes
Sorted polygons	0.12816	2.45	0.11583	90.38	0.00033	0.26	0.01200	9.36
Sorted nets	1.86198	35.57	1.29805	69.71	0.06443	3.46	0.49950	26.83
Sorted circles	0.00045	0.00009	0.00045	100	–	–	–	–
Sorted stripes	2.96081	56.56	2.01750	68.14	0.02568	0.87	0.91763	30.99
Earth hummocks	0.01670	0.32	–	–	–	–	0.01670	100
Peat hummocks	0.07093	1.35	0.07093	100	–	–	–	–
Non-sorted stripes	0.19608	3.75	0.00865	4.41	–	–	0.18743	95.59

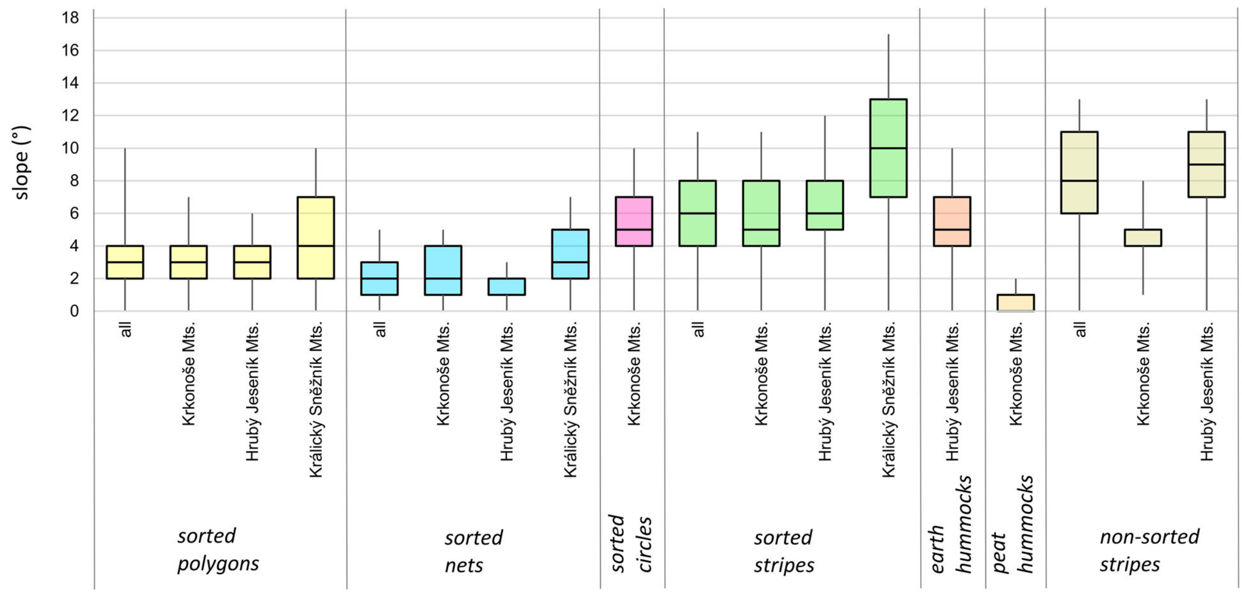

Figure 2. Boxplots showing differences in slope angle between different types of patterned ground among locations of the High Sudetes. The boxes show median values (thick horizontal line) and the first and third quartiles (bottom and top of boxes, respectively). Whiskers represent the minimum and maximum values, excluding outliers (values lying 1.5 interquartile ranges below and above the first and third quartiles, respectively).

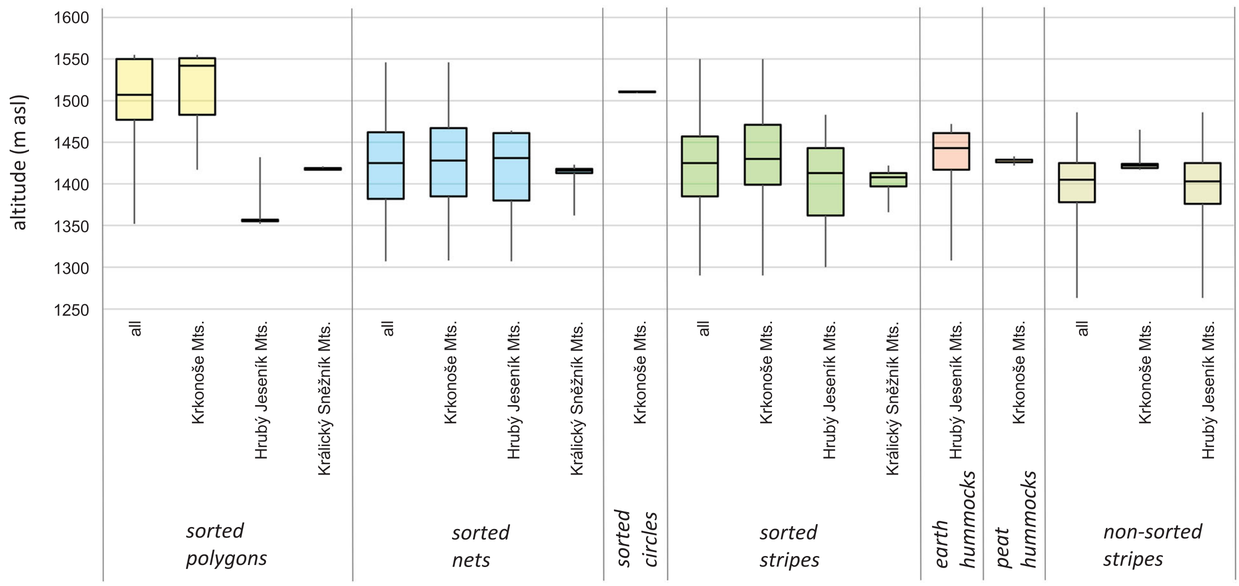

Figure 3. Boxplots showing differences in altitude between different types of patterned ground among locations of the High Sudetes. The boxes show median values (thick horizontal line) and the first and third quartiles (bottom and top of boxes, respectively). Whiskers represent minimum and maximum values, excluding outliers (values lying 1.5 interquartile ranges below and above the first and third quartiles, respectively).

elongate due to solifluction when slope angle increases, and change to sorted stripes on slopes with prevailing the angle from 4° to 8°. Sorted stripes (length: from a few metres to several tens of metres; width: 1.5–3.0 m; height: 0.1–0.2 m) are located at similar altitudes as sorted nets (1385–1457 m asl, Figure 3).

Non-sorted patterned ground occupies only 5.4% of the total patterned-ground area in the High Sudetes. While peat hummocks occur only in the Krkonoše Mts. (Main map; page 2), earth hummocks are developed exclusively in the Hrubý Jeseník Mts. (Main map; page 3). Peat hummocks (0.7–2.5 m in diameter) occur on flat surfaces (0–2°) between 1422 and 1433 m asl. Earth hummocks (length: 0.65–3.90 m; width: 0.55–2.30 m; height: 0.19–0.65 m) are mostly situated between 1417 and 1461 m asl on gentle slopes (4–7°), while on steeper slopes (6–11°) they are transformed by solifluction into non-sorted stripes (length: from a few metres to several tens of metres; width: 0.45–1.50 m; height: 0.15–0.40 m), which occur between 1376 and 1425 m asl (Figures 2 and 3).

From the viewpoint of altitudinal zonation, the sorted polygons are located at the summit parts, with more severe microclimate (*sensu* Washburn, 1979), followed by sorted nets at lower altitudes. Since these patterned-ground types are relict, they prove the existence of mountain periglacial zonation (*sensu* Harris, 1982; Niessen et al., 1992) in the High Sudetes during the last glacial period when these sorted polygons and nets were formed (Sekyra et al., 2002; Sekyra & Sekyra, 1995; Traczyk & Migoń, 2000). In addition, sorted polygons and nets prove the presence of permafrost at the time of their formation.

This paper presents the first map of the spatial distribution of patterned ground above the alpine timberline in the whole High Sudetes. Our uniform geomorphological mapping was carried out in all sub-regions of the High Sudetes (i.e. the Krkonoše Mts., the Králický Sněžník Mts. and the Hrubý Jeseník Mts.) in both the Czech Republic and Poland (Main map). The importance of the map is for palaeogeographical and palaeoenvironmental studies as well as for future environmental planning and nature protection management (e.g. protected area zoning, hiking trail managing, designing of footpaths, removing of non-indigenous vegetation overgrowing active patterned ground, etc.). The map can also serve as a validation dataset for automatic distribution modelling of patterned ground in mountain areas using statistical models and/or machine learning techniques.

Software

Mapping of patterned ground and the DEM analyses were carried out in ArcMap 10.3 (ESRI, 2014). The R language (R Development Core Team, 2008) in the interface of RStudio 1.1.453 (RStudio Team, 2016) was used for the statistical analyses. The final layout of the map set was produced in ArcGIS Pro (ESRI, 2017).

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ORCID

Marek Křížek http://orcid.org/0000-0001-5791-571X
David Krause http://orcid.org/0000-0001-5224-8954
Tomáš Uxa http://orcid.org/0000-0001-9911-6529
Zbyněk Engel http://orcid.org/0000-0002-5209-7823
Václav Treml http://orcid.org/0000-0001-5067-3308
Andrzej Traczyk http://orcid.org/0000-0002-1641-2021

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