Geomorphology 115 (2010) 109–116

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

Geodiversity of high-latitude landscapes in northern Finland

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ARTICLE INFO

Article history:
Received 28 May 2009
Received in revised form 8 September 2009
Accepted 26 September 2009
Available online 12 October 2009

Keywords:
Geodiversity
Biodiversity
Geomorphological mapping
Grid approach
Landscape scale
Subarctic

ABSTRACT

Geodiversity is a rather new, emerging topic in earth science. There is now increased awareness of our need to understand patterns of geodiversity in different landscapes facing global change. In this study, we systematically inventoried geodiversity and topographical parameters in an area of 285 km^2 in subarctic Finland. We quantified the spatial variation of geodiversity using four different measures and analysed the relationship between geodiversity and topography using a spatial grid system at a landscape scale (the size of the analysis window was 500×500 m). The number of different elements of geodiversity (total geodiversity) varied from 2 to 22 per grid cell. The spatial pattern of the total geodiversity, geomorphological process variability and geodiversity index were fairly similar, whereas of the other geodiversity measures, the measure of temporal diversity differed the most. Topographically, the high-diversity sites occurred in rather steep-sided valleys. Areas of high geodiversity reflect heterogeneous abiotic conditions where both erosion and accumulation processes play a major role in landscape development. The mapping of geodiversity may be indicative not only in the context of geomorphology, but also provide a focus for conservation initiatives. From a conservation point of view, the lack of wider knowledge of the distribution of geodiversity and its relationship to biodiversity hinders the protection of ecologically and geomorphologically valuable regions. Thus, we recommend that further studies focus on: (1) quantifying spatial patterns of geodiversity in different regions, (2) determining the key drivers that control the variability of geodiversity and (3) exploring the linkage between geodiversity and biodiversity.

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1. Introduction

Interest in the diversity of Earth's natural phenomena has increased dramatically during the past few decades. Basically, the broad concept of 'natural diversity' can be divided into two independent though complexly related elements: biodiversity and geodiversity. Particularly after the Earth Summit held in Rio de Janeiro in 1992, biodiversity has been the focus of numerous studies and research programmes worldwide (e.g. Pimm et al., 1995; Myers et al., 2000). The concept of geodiversity is rather new, however, and has developed under the shadow of biodiversity (Gray, 2004; Ibáñez et al., 2005; Gray, 2008). Although interest in the variability of geological and geomorphological features extends centuries back, the variety of earth materials, forms and processes has seldom been viewed as an entity. To fulfil this research deficiency in earth science, the idea of geodiversity has been increasingly used in the last two decades (e.g. Sharples, 1993; Gray, 2004).

The term geodiversity is used in different contexts and defined in various ways ranging from geological diversity to the variability of natural and anthropogenic features of a landscape (e.g. Johansson, 2000; Prosser, 2002; Stanley, 2003; Kozlowski, 2004). Gray (2004) proposed a generally accepted definition: 'the natural range (diversity) of geological (rocks, minerals, fossils), geomorphological (land form, physical processes) and soil features'. Later, Serrano and Ruiz-Flaño (2007a, b) included topography and elements of the hydrosphere in the diversity of abiotic nature. Research topics in geodiversity have mostly been related to conservation issues, which is axiomatic because of geodiversity's historical background and linkage to biodiversity (Gray, 2005; Burek and Prosser, 2008). Recently, awareness of the importance of assessing the impact of ongoing and future climate change on earth surface processes has increased. In alpine and high-latitude landscapes, there is a high risk of losing geodiversity with a warmer climate (see Fronzek et al., 2006).

Geodiversity studies usually focus on the evaluation of specific sites, geosites (Reynard and Panizza, 2005; Reynard and Coratza, 2007). Geosites are important for overall geodiversity and the protection of natural heritage (Gray, 2005; van Loon, 2008). However, geosites seldom provide information on the variability of earth materials, forms and processes in a given area. Thus, there exists a great need to study geodiversity in a spatial context (see Ibáñez et al., 2005; Serrano and Ruiz-Flaño, 2007a). Even though many have acknowledged the importance of measuring geodiversity (Kozlowski, 2004; Gray, 2004; Reynard and Panizza, 2005; Zouros, 2007; Pereira et al., 2007), studies that have explored the spatial variability of

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0169-555X/$ – see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.geomorph.2009.09.039

geodiversity are still largely lacking, particularly for high-altitude and latitude areas.

The aim of our study was to partly fill this gap by mapping and quantifying geodiversity in a high-latitude landscape, specifically, in an area of 285 km^2 in northern Finland. More precisely, our aims were: (1) to map the elements and to describe the spatial variation of geodiversity in a subarctic landscape; (2) to apply and test four measures of geodiversity, namely the total geodiversity, the variability of geomorphological processes, the temporal variability of the elements and the geodiversity index proposed by Serrano and Ruiz-Flaño (2007a); and (3) to explore the relationship between topography and geodiversity.

2. Study area

The study area is located in the northernmost region of Finnish Lapland (Fig. 1). Geologically, the area belongs to a Pre-Cambrian granulite complex ca. 1.9 billion years old (Meriläinen, 1976). The general relief of the area is governed by polygenetic bedrock topography formed by tectonic block movements and denudation phases over the past 25 million years (Kaitanen, 1989). The fell summits (420–640 m a.s.l.) are relatively flat and rounded, although preglacial weathering residuals, tors, are found in many places. During the Pleistocene glacial periods, continental ice sheets shaped the general topography and formed surficial glacigenic deposits. The deglaciation of the region began ca. 10000 years BP (uncalibrated), and the whole area was released from under the ice in about 200 years (Seppälä, 1980; Koskinen, 2005). During the Holocene, fluvial and cryogenic processes have mainly modified the land surface (Hjort, 2006; Luoto, 2007). The influence of humans on the topography has been very limited throughout history. The most widespread but indirect modification has been reindeer husbandry and its effect on topsoil erosion.

The area is located within the zone of permafrost (Fig. 1). The climate is subarctic and relatively continental even though the distance to the Arctic Ocean is only ca. 100 km. The mean annual air temperature (MAAT) was −1.7 °C, and the mean annual precipitation was 414 mm during the period from 1971 to 2000 (Drebs et al., 2002). The vegetation of the area is characterised by subalpine mountain birch forests (*Betula pubescens* ssp. *czerepanovii* (Orlova) Hämet-Ahti) and alpine heaths. Mires belong to the palsa and subalpine types (Luoto and Seppälä, 2002a). Hydrologically, the area is a typical subarctic region with a high but short-term flood peak (Luoto, 2007). The short and drastic spring floods are the result of rapid snowmelt and a lack of significant lake basins that would attenuate flood peaks (Mansikkaniemi, 1972).

3. Data and methods

3.1. Elements of geodiversity

In this study, we applied the classifications of Gray (2004) and of Serrano and Ruiz-Flaño (2007b) to determine the elements of geodiversity (Table 1). Consequently, we included the features of geology, geomorphology and hydrology in the list of elements, but omitted soil types (pedology) and topography. Soils were not mapped because of the difficulty in determining subsurface properties at the landscape scale. Topography was omitted because it is too difficult to determine unambiguously as an element of geodiversity (Serrano and Ruiz-Flaño, 2007b; Olaya, 2009). As a spatial study design, we used a spatial grid system at a mesoscale (the size of the analysis window = 500 × 500 m, $n = 1137$). This scale enables the use of various data sources, from detailed field surveys to rather coarse-scaled maps (Hengl, 2006; cf. Walsh et al., 1987). The mesoscale approach was chosen based on the size range of the detectable elements of geodiversity and the extent of the study area (285 km^2). Thus, fine-scale elements such as micro-landforms and minerals were not considered. Moreover, the large size range of the elements led to the utilisation of a simple mapping system (element either present or absent). Consequently, the aim was not to measure the abundance of the elements and related diversity indices (e.g. Ibáñez et al., 1995, 1998). The specific elements of geology and geomorphology were classified according to the national system of geomorphological mapping (Fogelberg and Seppälä, 1986; Seppälä, 2005a,b), which is based on international recommendations (Demek, 1972).

The elements of geodiversity were mapped using comprehensive field surveys, aerial photographs and various published data sources. The key data gathering methods for the geological and geomorphological elements were interpretation of orthorectified aerial photographs (OrtoCD, 2000) covering the whole study area (ground resolution = 1 m, planimetric root-mean-square error (RMSE) between different images = 18.0 m) and field surveys with a Global Positioning System (GPS) device (Garmin eTrex personal navigator with an accuracy of about 10 m; Garmin, Olathe, KS, USA) during the summers of 2002–2004 (Hjort, 2006). A total of 1112 (98%) of the 500 m grid squares were visited in the field. Stereoscopic interpretation of black-and-white aerial photographs (1:31 000; ground resolution ~0.5 m; photographed 1961 and 2001) and topographic maps (1:20000) were used in the preliminary mapping of the geological and geomorphological landforms. The base data for the geological elements were geological maps (1:400000; smallest detectable objects ~0.05 km^2) (Meriläinen, 1965; Kujansuu, 1981). Moreover, a digital surficial deposit map (grid size = 20 m; Hjort, 2006) was used in the determination of the Quaternary deposits. The hydrological elements were compiled using GIS databases (NSL Topographic Database, 2000; Sihvo, 2002) except for springs, which were mapped in the field. In addition, studies published from the area were used in the compilation of the data (e.g. Seppälä, 1993a,b; Luoto and Seppälä, 2000, 2002b; Hjort et al., 2007). The sizes of the smallest elements varied from 1 to 2 m for point elements (e.g. springs, ploughing blocks and tors) to ca. 5 m for areal elements (e.g. sand bars, patterned ground fields and deflation sites) (Luoto and Hjort, 2005; Hjort, 2006).

Next, the compiled data were used to produce four measures of geodiversity at a resolution of 500 × 500 m. First, the total number of different elements was calculated (total geodiversity). Second, the geomorphological elements were classified according to their genesis in order to determine the process variability of the study squares. The elements were classified into nine groups, and the total number of different processes present was calculated. Third, the mapped elements of geodiversity were classified according to their time of formation to determine the temporal variability of the elements in the study squares. In temporal classification, the elements were classified into six groups: (i) formation of rock type (Pre-Cambrian), (ii) long-term erosion and denudation phase (Pre-Cambrian–Pleistocene), (iii) Pleistocene glaciation, (iv) deglaciation of the Weichselian continental ice sheet, (v) Holocene and (vi) current or rather recent activity (i.e. process activity within the recent decade). This rough classification system was used because of the high number of specific elements, the difficulties in determining the age of pre-Holocene and polygenetic elements, and the geological history of Finland (e.g. Fogelberg and Seppälä, 1986). The last two groups partly overlap, but additional emphasis was given to the recent activity. Fourth, the geodiversity index (Gd) was computed by applying the formula of Serrano and Ruiz-Flaño (2007a,b):

$$Gd = Eg\, IR / \ln S \tag{1}$$

where Eg is the number of different elements in the study square (total diversity), IR is the roughness parameter (see Eq. (4) for definition), ln is the natural logarithm and S is the area of the square (ha).

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