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Geophysical anatomy of counter-slope scarps in sedimentary flysch rocks (Outer Western Carpathians)

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ABSTRACT

A multidisciplinary geophysical survey, consisting of electrical resistivity tomography (ERT), ground penetrating radar (GPR), shallow seismic refraction (SSR) and gravity survey (GS), was used to investigate the counter-slope scarps, one of the typical manifestations of the relaxed zones of rock massifs, and the possible initial stages of deep-seated landslides (DSLs). Two upper parts of the extensive DSLs within the Moravskoslezské Beskydy Mountains (Outer Western Carpathians – OWC) built by the sedimentary flysch rock were chosen as the testing sites. A combined geophysical survey on the flysch rocks was performed on both localities to enhance our present findings. The survey revealed that the ERT is able to reliably detect underground discontinuities, which are manifested at the ground surface by one of the typical landforms (tension cracks, trenches, pseudokarst sinkholes, double-crested ridges and counter-slope scarps). Previous studies suggested that bedrock discontinuities should be depicted by high-resistivity features within ERT surveying. According to SSR and GS, expected zones of weakened rock massif were not confirmed directly underneath the superficial landforms, but they were shifted. Based on the SSR and GS measurements, the depicted high-contrast transitions between high- and low-resistivity domains within the ERT profiles were newly identified as possible manifestation of bedrock discontinuities. The results of GPR measurements give only limited information on the sedimentary flysch rocks, due to shallow penetrating depth and locally strong signal attenuation. The combined results of multidisciplinary geophysical surveying confirmed an importance of employing more than one geophysical technique for integrated interpretations of measured data. Integrated interpretations of the measured geophysical data provided a new insight into massif disintegration and the geomorphic origin of the landforms related to the DSL.

1. Introduction

Relaxed zones of rock massifs often represent the initial stages of deep-seated landslide (DSL) development (Margielewski and Urban, 2003, 2005). This phenomenon is often connected with ridge disintegration and related slope processes, such as lateral spreading, toppling, sackung and rotational or translational sliding (Nemčok, 1972; Dikau et al., 1996; Agliardi et al., 2001; Nichol et al., 2002; Margielewski, 2006; Esposito et al., 2007; Crosta et al., 2013; Jomard et al., 2014). As a result of a combined effect of these processes, various typical landforms developed, such as exposed rocky headscarps, step-like slopes, back-tilted rock blocks, opened tension cracks, double-crested ridges, parallel trenches, pseudokarst-sinkholes, and crevice-type caves (Lenart et al., 2014). Most of these landforms have distinct geomorphic manifestations; however, they result from the processes that operate under the ground surface, i.e., (i) gravitational widening of joints with formation of crevice-type cave systems, and (ii) subsidence and lateral rotations of rock blocks (Pánek et al., 2010a, 2011a; Lenart et al., 2014). All the processes mentioned above disrupt bedrock and, together with favourable geology they may result in accelerated slope processes (Dikau et al., 1996; Geertsema et al., 2006; Hungr et al., 2001). This is why we often consider these landforms as the initial forms of DSLs (Dikau et al., 1996; Margielewski and Urban, 2003). Investigating these processes helps us to interpret and better understand factors controlling slope development.

Regarding the ages of DSLs, the ^{14}C data of tens of landslides in the Polish, Czech and Slovak Outer Flysch Carpathians mostly reveal the ages of the humid Holocene phases (Margielewski, 2003, 2006; Pánek et al., 2011a, 2013). The ages are mostly obtained from organic material in peat bogs, trench infills or landslide-dammed lakes.

In the present study, we focused on counter-slope (uphill-facing) scarps, which can provide evidence of subsurface gravitational processes within the sedimentary flysch rocks in mid-mountain regions. For the

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acquisition of the subsurface image of the underground structures, we applied a complex geophysical survey, consisting of DC resistivity imaging (ERT), electromagnetic high-frequency ground penetrating radar (GPR), shallow seismic refraction (SSR) with tomographic data-processing and gravity surveying (GS) (Schrott and Sass, 2008). The obtained geophysical data sets were processed to reveal possible evidence of the above-described processes and the resulting landforms. The results of the individual methods offer models with different information abilities, limited by the character of each investigated geophysical field (sensu Telford et al., 1990; Reynolds, 1997; Milsom, 2003).

We chose two upper parts of an extensive DSL within the Moravskoslezské Beskydy Mountains (Outer Western Carpathians – OWC) as the testing sites, where mass movements entirely dominate the slope development. Disintegration of mountain ridges is controlled by such slope processes, as reported in numerous geomorphological studies from the area of the OWC (Baroň et al., 2004; Lenart et al., 2014; Hradecký and Pánek, 2008; Margielewski, 2001, 2006; Margielewski and Urban, 2003, 2005; Pánek et al., 2007, 2009, 2010a, 2011a). Similar localities were already studied using formal techniques: geomorphological mapping, ERT or even trenching (Lenart et al., 2014; Pánek et al., 2011a). In the present study, we performed, for the first time, the investigation by means of combined multidisciplinary geophysical survey, which offers a better possibility to reveal a massif relaxation and its structure.

The present paper methodically focuses on complex multidisciplinary surveying using four different geophysical techniques. In previous studies, the researchers primarily used the ERT technique as the only method for DSL surveying (Pánek et al., 2007, 2010a,b, 2011a,b, 2014; Šilhán, 2010; Tábořík, 2012; Lenart et al., 2014). There are only few papers concerning the combined geophysical survey of DSLs within the OWC flysch rocks – e.g., Pánek et al. (2011a) performed a complex survey by means of ERT, SSR and symmetric resistivity profiling (symmetric RP). The aim of the present study is, also, to assess the ability of geophysical techniques to reveal the structure and slope development within DSLs in the sedimentary flysch rocks environment.

2. Geological and geomorphological setting

Both of the investigated sites are situated within the western portion of the Carpathian mountain range (OWC, The Moravskoslezské Beskydy Mts.; Fig. 1), which is formed by a flysch of Mesozoic (Late Jurassic) to Paleogene/Neogene (Early Miocene) sedimentary rocks. During the Lower and the Middle Miocene alpine orogeny phases, these sediments were folded and thrusted onto the foredeep in the northern direction, forming several nappes (Menčík et al., 1983). Both of the investigated sites are situated in the culmination portion of the Godula flysch nappe (Fig. 1), which is created by the Godula formation. The sedimentary strata consist of thick-bedded sandstones or conglomerates alternating with very thin-bedded claystones or siltstones with clay mineral content (Menčík et al., 1983; Pánek et al., 2011a). During the Miocene, the rocks were disrupted by joints and faults, trending in the E–W, NW–SE, and NE–SW directions (Menčík et al., 1983; Krejčí et al., 2002; Bubík et al., 2004) as well as the WNW–ESE direction (Menčík et al., 1983; Pánek and Duras, 2002).

Morphologically, the ridges are formed asymmetrically. Because of the inclination of the strata slightly to the south-east, the northern slopes are short but steep, predisposed by the frontal parts of beds, whereas the southern slopes are long and gentle, formed on bedding planes. Such bedrock structure, together with the effects of tectonics (faults, crevices and tension cracks), predispose the mountain ridges to a slope development controlled mainly by the gravitational slope movements (Lenart et al., 2014). Weak and semi-plastic claystones act as shear surfaces for slope movements of more rigid overlying sandstone formations. Lithology and high slope gradient (frequently 30–40°) thus determine the conditions, which cause relatively high vulnerability to DSL development.

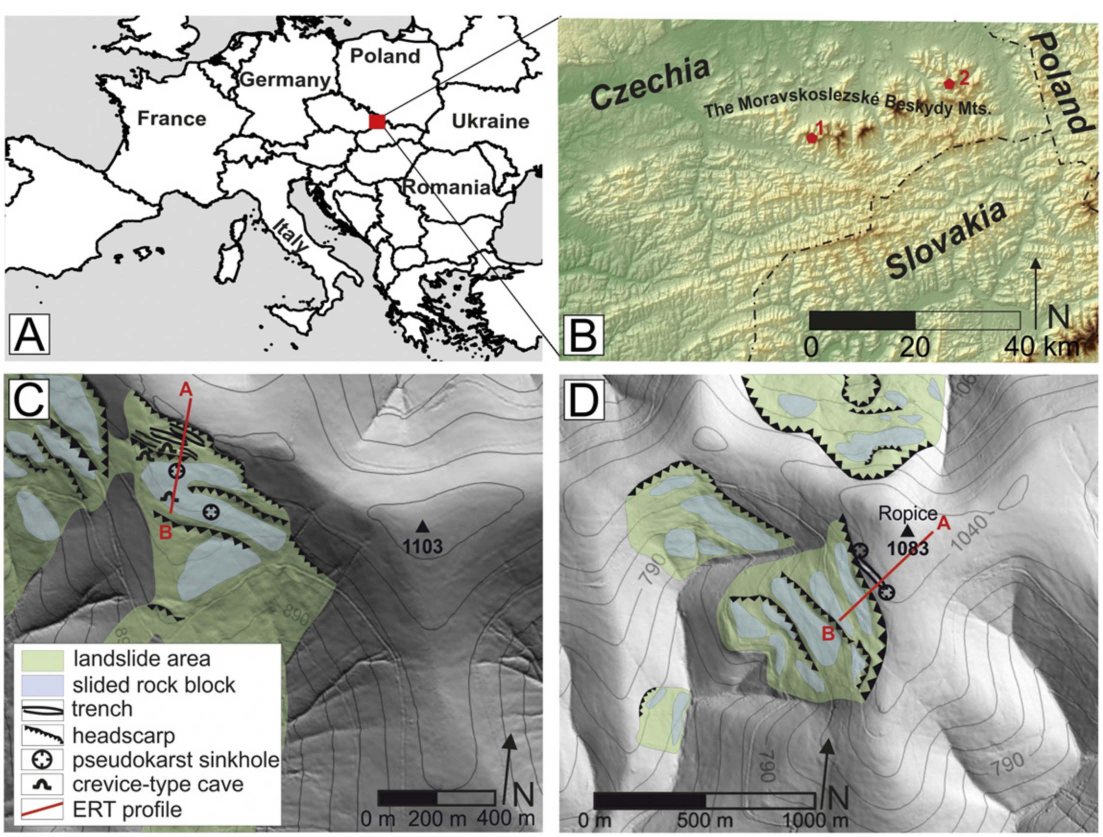

Fig. 1. Studied sites. (A, B) Overall situation. (C) Záryje site with the location of the Záryje 1A geophysical profile. (D) Ropice site with the location of the Ropice 1 geophysical profile.