Geomorphology 322 (2018) 175–187

Contents lists available at ScienceDirect

Geomorphology

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

# Sackung and enigmatic mass movement folds on a structurally-controlled mountain ridge

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ARTICLE INFO

*Article history:*
Received 18 June 2018
Received in revised form 4 September 2018
Accepted 4 September 2018
Available online 05 September 2018

*Keywords:*
Slope tectonics
Transpression
Ramp-flat thrust
DSGSDs
Sackung
LiDAR
Near-surface geophysics
Flysch Carpathians

ABSTRACT

The recently emerged concept of "slope tectonics" suggests that mass movement processes can produce structures similar in morphological expression to that of extensional, strike-slip and compressional tectonic deformations. Further, there has long been debate about the (tectonic or gravitational) origin of lineaments found on hillslopes. Here we present cases of where geological structure and inherited tectonic structures have preconditioned the development of mass movements and creation of slope tectonic features on a monoclinal ridge (Smrk Mt.) in the Outer Western Carpathians, Czechia. Geomorphic mapping from LiDAR-derived topography, structural measurements, electrical resistivity tomography and ground penetrating radar, were used to map synthetic and antithetic scarps, thrusts, and folds, and assess their relation to geological and tectonic structures. The scarps are found to be strongly related to transverse (NNW to NNE trending) inherited normal and strike-slip faults and mainly cross-cut the topography of the mountain ridge. Some of the folds are thought to have originated from buckling or compression in the distal parts of landslides. In other places, transpressional folds have developed oblique to major lateral shear surfaces interpreted to be sackung (mass movement scarps) that have been inherited from tectonic faults. The transpressional folds developed due to localized contraction along bends in the lateral shear surface as mass movement proceeded. Ramp-flat thrust folds developed in the compressional parts of landslides, where the landslide intersects with slope parallel sackung and/or inherited fault planes inclined to the slope. Altogether, this study demonstrates a connection between kinematics of deep-seated gravitational slope deformations (DSGSDs), shallower landslides and the origin of transpressive, ramp-flat thrust, and detachment structures in rock slopes.


## 1. Introduction

Mass movements often produce structures which are morphologically similar to tectonic features (Bishop and Norris, 1986; Fleming and Johnson, 1989; Jaboyedoff et al., 2011, 2013), and this similarity has previously led to misinterpretations of the origin of both mass movement and tectonic structures in mountainous topography (Hart et al., 2012; Hippolyte et al., 2006). 'Slope tectonics' was recently adopted as an umbrella term for a variety of slope forms that are induced or controlled by gravitational processes (i.e. mass movements) but having a morphology comparable in form to those created by tectonic activity (Jaboyedoff et al., 2011). Many of these features are common to deep-seated gravitational slope deformations (DSGSDs), which are deformations of slopes or entire ridges that typically develop by continuous creep deformation (Agliardi et al., 2001), but can evolve to more rapid failures (Pánek and Klimeš, 2016).

Jaboyedoff et al. (2013) have described a range of slope-tectonic features and noted where on the slope and under which stress regimes they typically develop: Double-crested ridges, sets of uphill- and downhill-facing scarps (i.e. sackung), and normal faults are produced in extensional regimes typically present in the upper parts of a slope; toppling, secondary (minor) scarps, folds and bulges are common in the intermediate parts of a slope; and folds and thrust faults may be present towards the slope toe where compressive stresses develop. Features associated with 'strike-slip' movement on the lateral margins of a landslide have also been described by Fleming and Johnson (1989), and folding related to gravitational thrust-faulting has been described by Baroň et al. (2006) and Jaboyedoff et al. (2011). Herein we extend the existing range of known slope tectonic features by describing types of mass movement forms associated with DSGSDs that have not previously been described. We interpret the stress-regimes responsible for these features and the geological preconditions that have facilitated

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https://doi.org/10.1016/j.geomorph.2018.09.004
0169-555X/

the development of these structures. Through LiDAR-based geomorphic mapping, field-based structural measurements, geophysical sounding, and dating, our objectives are the following:

1) Map and describe slope tectonic features and other mass movements encountered at Smrk Mountain in the Czech Outer Western Carpathians (Fig. 1);
2) Infer how the spatially coincident tectonic features, overall tectonic setting, and the monoclinal structure of the study area may have facilitated these mass movement phenomena;
3) Comment on the evolution of these features in terms of their timing and cross-cutting relationships.

In this study we adopt the terminology of Hippolyte et al. (2009, 2012) to distinguish between faults of pure tectonic origin, referred to here as 'tectonic faults' and those produced or reactivated by gravitation (i.e. mass movement), referred to here as 'sackung faults'. A paucity of outcrops in the densely forested study area means we rely largely on surface morphology observations and geophysical imaging of the subsurface to develop and validate the conceptual slope-tectonic models presented herein.

## 2. Setting

The study area is located in the Moravskoslezské Beskydy Mountains (MB), the highest part of the Outer Western Carpathians (OWC) in Czechia (Fig. 1A). The nappe structure of the MB is formed of a sequence of Upper Cretaceous (Cenomanian, Turonian) flysch sediments of the Silesian Unit which originated ~15 Ma ago during Miocene thrusting (Menčík et al., 1983).

The study area comprises a densely forested monoclinal ridge, Smrk Mt. (1276 m a.s.l.), which is bounded by the deeply incised valleys (of local relief >500 m) of the Ostravice and Čeladenka rivers. The ridge is formed of thick-bedded flysch of the Godula Formation (sandstone beds with thickness mostly >1 m) sandwiched between predominantly thin-bedded flysch (predominantly claystone), that outcrops along the northern and southern foot slopes of the ridge (Menčík et al., 1983; Fig. 1B).

The flysch bedrock dips gently (<20°) to the south-east, and is disrupted by several tectonic joint and fault sets, that have two dominant directions of strike: E–W to NE–SW directions perpendicular to the vergence of Miocene nappes (Fig. 1B), and NW–SE to NNE–SSW

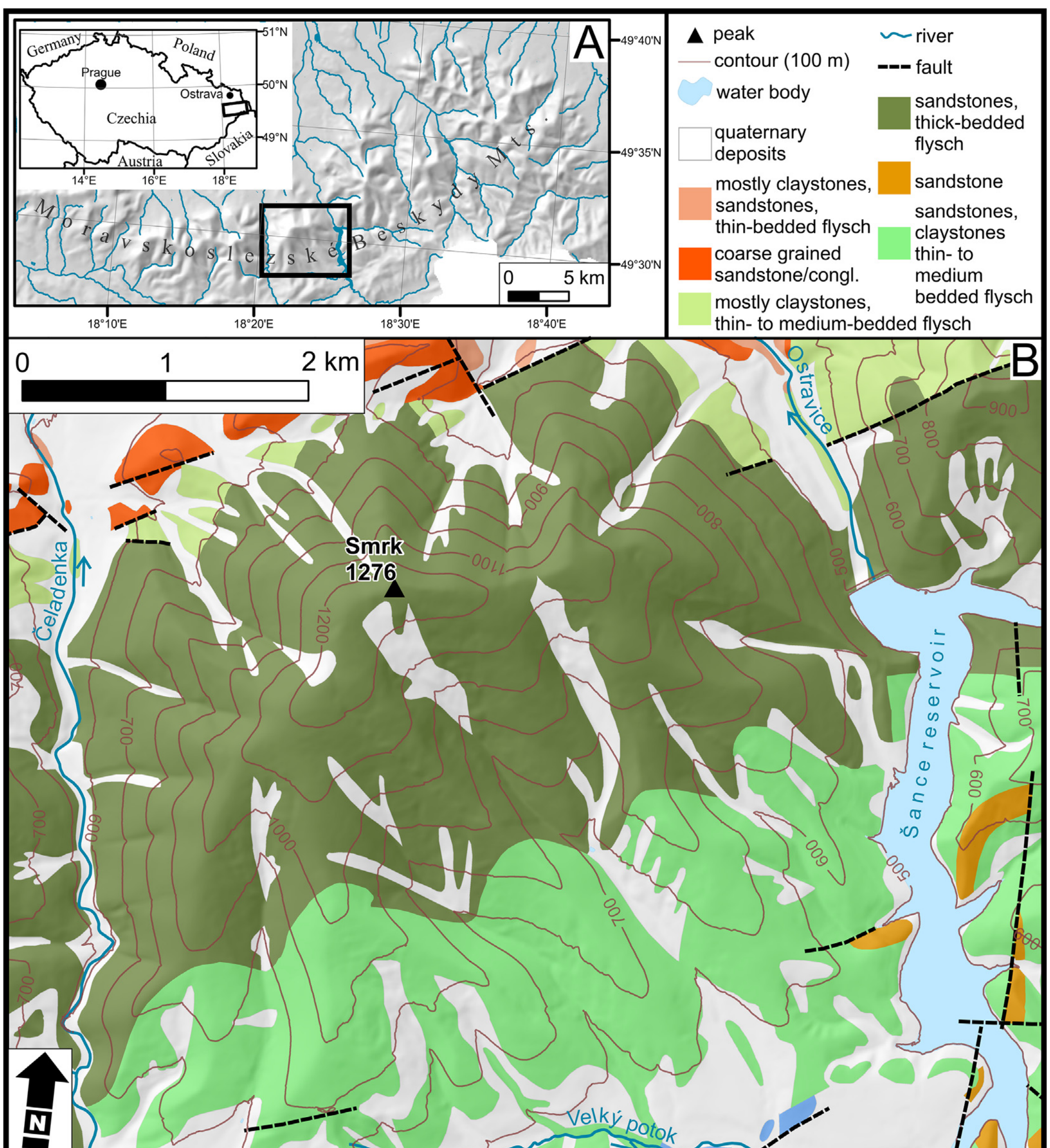


**Fig. 1.** A) Location of the study area. B) Geological map of the study area. Modified after Czech Geological Survey (2015).