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Coastal cliffs, rock-slope failures and Late Quaternary transgressions of the Black Sea along southern Crimea

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ABSTRACT

Rock-slope failures represent a significant hazard along global coastlines, but their chronology remains poorly documented. Here, we focus on the geomorphology and chronology of giant rockslides affecting the Crimean Mountains along the Black Sea coast. Geomorphic evidence suggests that high (>100 m) limestone cliffs flanking the southern slopes of the Crimean Mountains are scarps of rockslides nested within larger deep-seated gravitational slope deformations (DSGSDs). Such pervasive slope failures originated due to lateral spreading of intensively faulted Late Jurassic carbonate blocks moving atop weak/plastic Late Triassic flysch and tuff layers. By introducing a dating strategy relying on the combination of the uranium-thorium dating (U-Th) of exposed calcareous speleothems covering the landslide scarps with the ^{36}Cl exposure dating of rock walls, we are able to approximate the time interval between the origin of incipient crevices and the final collapse of limestone blocks that exposed the cliff faces. For the three representative large-scale rockslides between the towns of Foros and Yalta, the initiation of the DSGSDs as evidenced by the widening of crevices and the onset of speleothem accumulation was >300 ka BP, but the recent cliff morphology along the coast is the result of Late Pleistocene/Holocene failures spanning ~20–0.5 ka BP. The exposures of rockslide scarps occurred mostly at ~20–15, ~8, ~5–4 and ~2–0.5 ka, which substantially coincide with the last major Black Sea transgressions and/or more humid Holocene intervals. Our study suggests that before ultimate fast and/or catastrophic slope failures, the relaxation of rock massifs correlative with karstification, cracks opening, and incipient sliding lasted on the order of 10^4–10^5 years. Rapid Late Glacial/Holocene transgressions of the Black Sea likely represented the last impulse for the collapse of limestone blocks and the origin of giant rockslides, simultaneously affecting the majority of the SW coast of the Crimean Peninsula.

1. Introduction

Although the presence of major landslides within coastal zones of oceans and large lakes is well known (Badger and Watters, 2004; Bromhead and Ibsen, 2004; Bird, 2008; Hildenbrand et al., 2012; Mather et al., 2014), their chronology and relations to Late Quaternary environmental changes have been poorly documented. The majority of landslide-dating studies have been hitherto concentrated on inland mountain areas (e.g., Soldati et al., 2004; Prager et al., 2009; Ivy-Ochs et al., 2009; Pánek et al., 2013; Yuan et al., 2013; Ballantyne et al., 2014; La Husen et al., 2016), with only a few attempts to constrain the long-term evolution of coastal landslides (Recorbet et al., 2010; Barlow et al., 2016; Pánek et al., 2016; Crosta et al., 2017; Schleier et al., 2017). However, there are opportunities to acquire better knowledge of the long-term dynamics of landslides related to neotectonics, palaeoseismic history, climate change and sea-level oscillation along coastlines. In such a respect, what can be considered unique natural laboratories are water bodies characterized by frequent, high magnitude oscillations during the Late Quaternary, such as some proglacial lakes (Glasser et al., 2016) or epicontinental seas (Tudryn et al., 2016). The latter case involves the well-known examples of the Caspian Sea and

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Black Sea, which were once connected as the Ponto-Caspian Basin and demonstrated frequent transgressive/regressive phases during the Late Quaternary (Sorokin, 2011; Tudryn et al., 2013, 2016). Recently published evidence of massive landslides along the Late Pleistocene highstands of the Caspian Sea (Pánek et al., 2016) raises the question of whether similar changes in water levels caused comparative large-scale slope instabilities along the adjacent, but steeper and geologically different Black Sea coast.

The southern extent of the Crimean Peninsula, which hosts the pronounced limestone cliffs of the Crimean Mountains, represents one of the most landslide-prone areas along the entire Black Sea coastline (Nikonov and Sergejev, 1996; Shestopalov et al., 2008; Pánek et al., 2009a). Although rock-slope failures represent important natural hazards and a first-order geomorphic imprint in this area, only few studies address their chronological reconstructions (Pánek et al., 2009a) and most of them are concerned with dendrochronologically inferred historical (<500 years) movements (Šilhán et al., 2012, 2013, 2015, 2016). Therefore, the time frame and recurrence interval of major mass movements along the southern Crimea are virtually unknown, which complicates the evaluation of the probability of landslide hazards and general understanding of the coastal landscape dynamics.

For the classification of mass movements described in this study, we mostly follow the widely used method of Cruden and Varnes (1996), which was recently updated by Hungr et al. (2014). As an umbrella term for all failures affecting bedrock, we use the term "rock-slope failures" (Jarman, 2006). Large-scale, non-catastrophic mass movements affecting vast portions of coastal slopes within the Crimean Mountains, which are characterized by specific linear morphostructures such as scarps, opened cracks and grabens, are termed "deep-seated gravitational slope deformations" (DSGSDs; Agliardi et al., 2001). We generally consider "rockslides" to be relatively fast rock-slope failures along well-defined failure surfaces that leave a clearly recognizable head scarp and failed mass with various degrees of fragmentation (Weidinger et al., 2014).

The chronological analysis of different mass movement types of widely differing ages and genesis requires the combination of several absolute dating methods. Guided by geomorphic mapping, we apply a combination of uranium-thorium (U-Th) and surface exposure (^{36}Cl) dating, in order to obtain the evidence of the Quaternary evolution of rock-slope failures flanking the south-western tip of the Crimean Mountains. Through the significant extension and update of our previous study (Pánek et al., 2009a), our primary objectives are as follows:

1) to present geomorphic evidence of the large-scale slope instabilities affecting the high limestone cliffs in SW Crimea,
2) to reconstruct the timing of rock-slope failures to attempt to define the chronological framework of both the pre-failure stage and final collapses, and
3) to discuss the possible causes of giant rockslides with special attention to the correlation of the obtained ages with the Late Quaternary history of the water level of the Black Sea.

2. Regional settings

The southern coast of the Crimean Peninsula is a part of the Crimean Mountains, which belong to the Caucasus-Crimean fold-and-thrust belt fringing the northern Black Sea (Fig. 1). The area originated as a response to the deformation of the tectonic boundary between the Black Sea domain and the East European Platform during Mesozoic-Cenozoic Alpine orogenesis (Muratov et al., 1984; Nikishin et al., 2001; Saintot et al., 1999). The main mountain-building events occurred during the Late Cimmerian orogeny (Early Cretaceous) followed by Eocene-Oligocene uplift, which is when the gross recent topography of the area was created (Pánek et al., 2009b). The lithology of the mountain region largely consists of a thick (>1 km) Late Jurassic carbonate sequence underlain by weak Late Triassic/Early Jurassic flysch and tuff with occasional Middle Jurassic intrusions (Derenyuk et al., 1984, Fig. 1). The physiographical character of the mountains is exhibited largely by 1) extensive elevated karst plateaus (locally known as yaylas), 2) steep southern slopes forming limestone cliffs and 3) relatively gently inclined flysch foothills forming narrow strip between the limestone cliffs and the Black Sea (Fig. 1).

The target area of this study is an ~25 km long coastal strip of the SW Crimean Peninsula, which is topographically the most exposed part of the Crimean Mountains between approximately 33°44.3′ E and 34°4.0′ E (Fig. 1). This area includes one of the highest altitudes of the Crimean Mountains (>1200 m a. s. l.) and up to 400 m high limestone cliffs rising nearly immediately above the Black Sea coast (Fig. 1). This sector of the Crimean coast is highly prone to mass movements, especially spreading, rockfalls, landslides and debris flows (Pasynkov et al., 1992; Nikonov and Sergejev, 1996; Pánek et al., 2009a; Šilhán et al., 2012, 2013, 2015, 2016). This susceptibility to mass movements results from the unstable lithological and tectonic structure of the slopes, intense karstification, abundant precipitation (>1000 mm year^{-1}) and active seismicity. The epicentres of historical earthquakes are distributed mainly offshore and along the coastal strip. To date, the most destructive historical seismic events were two successive earthquakes in 1927 with M_w ~6.0 and M_w ~6.8. They triggered more than 80 mostly small rock-slope failures, which were primarily rockfalls (Nikonov and Sergejev, 1996).

3. Methods

3.1. Geomorphic mapping

Geomorphic mapping of the SW coastal strip of the Crimean Mountains was performed in an area of ~40 km^2 using 1 arc-second SRTM digital elevation data at ~30-m resolution (http://www2.jpl.nasa.gov/srtm), QuickBird and Google Earth™ imagery and several field campaigns during the years 2007–2013 (Fig. 1). Speleological techniques served to estimate the depths of open cracks. The major concerns were attributed to three representative rock-slope failure complexes, namely, Foros, Morcheka and Shan-Kaya (Fig. 1). These sites were selected due to well-developed landform assemblages related to mass movements and the widespread presence of datable elements, including speleothems and fresh, non-eroded scarp surfaces. The mapping focused on the identification of landforms and structures diagnostic of rock-slope failures, such as scarps, grabens, open cracks, boulder accumulations, and bulged toes. Special attention was also paid to karst features spatially related to slope failures, e.g., collapsed sinkholes, unroofed caves and speleothems along the edges of karst plateaus. Furthermore, we performed subsurface surveys of several crevice-type caves indicating the retrogression of rockslides and/or DSGSDs. The discovery of the widespread occurrence of exposed ("dead") speleothems on rockslide scarps directed our dating strategy towards the combination of U-Th and ^{36}Cl exposure dating. Therefore, the field surveys also focused on the selection of the most suitable sites for absolute dating.

3.2. Dating strategy

Two datable features of the rock slope features in the study area include 1) exposed ("dead") speleothems covering rockslide scarps and the walls of widened cracks and 2) rockslide scarps, which