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Reconstruction of retreating mass wasting in response to progressive slope steepening of the northeastern Cretan margin, eastern Mediterranean

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ABSTRACT

In this study we aim on a reconstruction of mechanisms and kinematics of slope-failure and mass-movement processes along the northeastern slope of Crete in the Hellenic forearc, eastern Mediterranean. Here, subsidence of the forearc basin and the uplift of the island of Crete cause ongoing steepening of the slope in-between. The high level of neotectonic activity in this region is expected to exert a key role in slope-failure development. Newly acquired reflection seismic data from the upper slope region reveal an intact sediment cover while the lower slope is devoid of both intact strata and mass-transport deposits (MTDs). In a mid-slope position, however, we found evidence for a ~4-km³-sized landslide complex that comprises several MTDs from translational transport of coherent sediment bodies over short distances. Morphometric analysis of these MTDs and their source scars indicates that this part of the northeast Cretan slope can be characterized as a cohesive slope. Furthermore, we reconstruct retrogressive development for this complex and determine a critical slope angle for both pre-conditioning of failure and subsequent landslide deposition near source scars. Consequently, data imply that the investigated shallower slope is stable due to low angles in the order of 3°, whereas 5°-inclined mid-slope portions favour both slope destabilization and landslide deposition. The failed mid-slope parts are dominated by sediment truncations from faults almost correlating with the orientation of head- and sidewalls of scars. We suggest that cohesive landslides and MTDs are generated and preserved, respectively, in such critical slope regions. If once generated, cohesive landslides reach the lower slope further downslope that exceeds the threshold gradient for MTD deposition (~5°), they are transported all the way down to the foot of the slope and disintegrate to mass flows. From these observations we suggest that the mass-wasting history of the investigated Cretan slope area over a longer period of time is characterized by repeated sediment erosion and transport into the deeper Cretan Sea basin. The relocation of the critical slope portion in upslope direction and therefore recurrence of mass-wasting events is thereby likely controlled by the progressive steepening of the slope. This mechanism and restriction of sediment failure to narrow, critically-inclined and relocating slope portions likely explains how such an active margin setting can exhibit only scarce findings of MTDs on the slope despite an expected, extensive and widespread mass wasting.

1. Introduction

It is generally accepted that repeated mass movements can erode a significant amount of submarine slope sediment through time and thus strongly affect slope morphology (e.g., Leeder, 1999; Canals et al., 2004; Haflidason et al., 2004; Urgeles et al., 2006). The mechanical behaviour of sediments and slope geometry thereby exert key roles in failure development and also have a high impact on the mass-movement transport mechanisms, which can occur either in a cohesive or disintegrative fashion (e.g., Locat and Lee, 2002; McAdoo et al., 2000). McAdoo et al. (2000, 2004) have shown that mass movements along active margin slopes bearing cohesive sediments often consist of compact landslides or slumps of low recurrence as these slopes can be of high resistance against shearing. Such cohesive landslides are of relatively small volumes and can have short runouts (e.g., Hampton et al., 1996 and Lee et al., 2007). Disintegration of landslides during longer runout as well as failure in sediments of non- or less-cohesive character can result in mass flows (e.g., Gee et al., 1999; Masson et al., 2006; Lee et al., 2007). Morphometric analyses of mass-transport deposits (MTDs), source scars and the adjacent slopes of cohesive landslides compared to mass flows indicate that they can strongly differ in scar geometry, headwall height and gradient, the gradient of the adjacent slope, as well as the mass-movement size and runout distance (McAdoo et al., 2000; Haflidason et al., 2003). Therefore, morphometric measurements on scars and MTDs can be used to reconstruct failure and transport kinematics as well as the

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mechanical behaviour of sediment during failure and transport (McAdoo et al., 2000).

The northeastern margin of Crete represents the southern border of the Cretan Sea submarine basin (Fig. 1A) and is an example that evidences only some scattered landslide scars and MTDs on an active margin slope. The detected pattern of MTDs on the slope comprises slides as well as debrites with volumes in the order of ≤0.5 to ≥2.0 km³ (e.g., Chronis et al., 2000; Kopf et al., 2006, 2007; Strozyk et al., 2009). Seismic data presented by Kopf et al. (2006) suggest the presence of stacked MTDs also in the deeper Cretan Sea sub-basins (i.e. the Kamilonisi and Heraklion Basin). However, the scarce findings of MTDs along the slope contrast the expectation of a diffuse and extensive mass-movement pattern related to the region's high neotectonic activity (e.g. earthquakes and tectonic movement), as characteristic for active margin settings. The high shear resistance of the cohesive, consolidated Cretan slope sediment is proposed being the responsible mechanism restricting a higher frequency of slope collapse (Chronis et al., 2000; Kopf et al., 2006, 2007).

The aim of this study is (i) an identification and detailed description of a cluster of MTDs on the northeastern Cretan slope, (ii) to measure proportions of MTDs, their source scars and the adjacent intact slope supported by morphometric analyses of this features, (iii) a determination of mass-movement types, runout distances and transport mechanisms, and (iv) to evaluate critical slope angles for sediment stability and pre-conditioning for its destabilization. Our study is based on the interpretation of multi-channel reflection seismic profiles and bathymetric data recorded during the 2006 CRESTS (Cretan Sea Tectonics and Sedimentology) cruise aboard R/V Poseidon. We also compare our findings to the concept of morphometric analysis of slope failures, and discuss the results in terms of slope morphology and tectonic movement representing pre-conditioning factors for mass wasting in such active margin environments.

2. Regional setting

The Cretan Sea basin represents the large forearc basin of the Hellenic subduction zone (McKenzie, 1978; Le Pichon and Angelier, 1979; Fig. 1A). This elongated, east–west-trending, almost north–south-extensional forearc depression is bordered to the north by the volcanic arc and to the south by the island of Crete (Fig. 1A and B), which is an exhumed horst structure (Bonneau, 1984) and still being uplifted (i.e. ≥6 mm a^{-1}; e.g., Ganas and Parsons, 2009 and references therein). Extension and subsidence of the basin is reconstructed to a last main creation phase during the Late Miocene and Pliocene, while it is proposed to have decreased since that time (Meulenkamp et al., 1988; Mascle and Martin, 1990). However, several surveys indicated recent fault activity and micro-seismicity in the southern Cretan Sea and have confirmed that the tectonic system is still active today (e.g. Lykousis et al., 1995; Perissoratis and Papadopoulos, 1999). Subsidence rates in the forearc region increase from the west to the east, likely associated to an increase of the dip of the African slab subduction to the east (e.g. Angelier et al., 1982; Meier et al., 2004). The resulting tectonic deformation to a southwest–northeast-striking half graben system (Fig. 1B) as well as Cretan Sea basin subsidence caused the formation of several large sub-basins, of which the Kamilonisi Basin is one of the deepest with up to 2500 m water depth (Fig. 1B; e.g. Stavrakakis et al., 2000). Major faults associated with these sub-basins as well as the Cretan Sea basin extension trend approximately northeast–southwest (Angelier et al., 1982; Mascle and Martin, 1990). A second system of faults trends

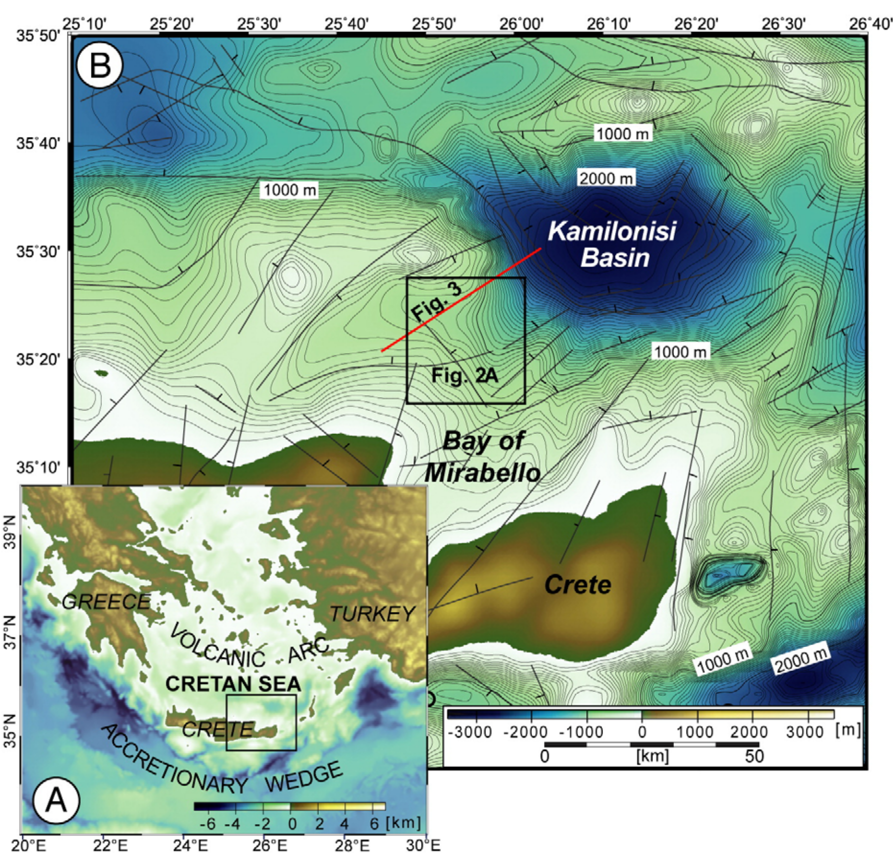

Fig. 1. A: Bathymetry map of the eastern Mediterranean active margin. The black box indicates the location of the study site and surroundings in the southern Cretan Sea (B); B: bathymetry map of the study site and surroundings on the northeastern margin of Crete, north of the Bay of Mirabello and southwest of the Kamilonisi Basin. Thin lines represent relief counter lines in 50-m intervals. Thick black lines indicate major faults in the southern Cretan Sea interpreted and compiled after Mascle and Martin (1990) and Angelier et al. (1982). The red line indicate the location of seismic profile GeoB06-133, the black box the outlines the study site in the mid-slope region (Fig. 2).