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Geomorphologic features related to gravitational collapse: Submarine landsliding to lateral spreading on a Late Miocene–Quaternary slope (SE Crete, eastern Mediterranean)

Tiago M. Alves [a,*], Sérgio D.N. Lourenço [b]

[a] 3D Seismic Lab, School of Earth and Ocean Sciences, Cardiff University, Cardiff CF10 3YE, United Kingdom
[b] Earth Surface Processes Research Group, School of Earth and Ocean Sciences, Cardiff University, Cardiff CF10 3YE, United Kingdom

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ABSTRACT

Detailed geological mapping, complemented by sedimentary facies analysis, photomosaics and topographic measurements (height, width) allowed the investigation of the geomorphological features related to the Late Miocene–Quaternary gravitational collapse of a palaeoslope located in SE Crete (eastern Mediterranean). In the study area, carbonate megablocks indicative of submarine landsliding during the Late Miocene alternate with collapse features more typical of subaerial settings; the latter generated after a major event of tectonic uplift initiated in Crete during the Early-mid Pliocene. Submarine features typically show basal shear zones, rather than planes, generated in near-seafloor strata deformed in ductile form during the gravitational collapse of the megablocks. The lithology of failed carbonate strata differs from that of their basal shear surfaces, a characteristic providing a reliable estimate for the degree and styles of basal deformation during submarine slope instability. Styles of submarine collapse include, by order of magnitude; (i) lateral spreading of fractured segments of fan cones and carbonate sheet flows, eventually transported 100s of metres downslope; (ii) aperture of ravines and chasms in gravitationally unstable fan cones and boulder conglomerates; (iii) gliding of megablocks over a ductile basal layer through a distance of up to several kilometres; and (iv) rolling of subcircular blocks, often within a debris-flow matrix in fan cones and deltas, or embedded in slope siliciclastic strata. This work highlights the existence of prominent 2–10 m basal shear zones in strata underneath the larger megablocks deposited on marine slope strata. Basal shear zones comprise a melange of reworked conglomerates and breccia clasts from overlying megablocks, large ripped blocks of rock and faulted near-seafloor strata, at places showing remnant beds and sand injection features. Consequently, the outcrop data show an average 5:1 ratio between the maximum observed thickness of megablocks and the thickness of basal shear zones (R), a value of similar magnitude to published examples from offshore landslides.

1. Introduction

Time-dependent variations in the shear-strength limits of susceptible subsurface strata are known to trigger seafloor instabilities (Hampton et al., 1996). Submarine failures occur firstly as low-angle faults over a discrete surface (or basal shear plane) before total, partial, or limited remobilisation of seafloor strata occurs (Legros, 2002; Frey-Martinez et al., 2006). Within a wider spectrum of morphologies, Frey-Martinez et al. (2006) considered two end-members for submarine landslides: i) a frontally-confined type, where the landslide mass is buttressed against a frontal ramp and it does not abandon the basal shear surface, and ii) a frontally-emergent type, in which the landslide mass ramps out of the basal shear surface and is free to travel long distances on a unconfined slope. In the latter type, debris-flow transport — occurring over a near-seafloor shear plane that is often irregular or indented — can reach distances of more than 100 km (Hühnerbach and Masson, 2004).

In contrast to their offshore counterparts, onshore landslides are translated through average distances of only 10s of metres to a maximum of a few kilometres, commonly above single or composite slip planes (Varnes, 1978; Greb and Weisenfluh, 1996). Basal slip planes of subaerial landslides are mostly submetric, comprising weak strata with particular geotechnical properties, such as plastic shales, undercompacted layers (lithological bands), permeable layers subjected to fluid flow, or weakness planes in rock formations, e.g., lithogenetic fissures, fractures due to unloading of a rock massif and tectonic faults (Shibakova et al., 1977; Nemec, 1990). In submarine environments, basal shear surfaces, or slip planes, of submarine landslides are particularly hard to sample, being scarcely exposed and often composed of hardened (cohesive) lithologies (e.g., Lykousis et

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* Corresponding author. Tel.: +44 29 20874830; fax: +44 29 20874326.
E-mail address: alvest@cardiff.ac.uk (T.M. Alves).

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al., 2003; Flemings et al., 2005), partly a result of technical difficulties in coring harder nonclayey sediments. Well documented basal shear surfaces record meagre thicknesses of 1–2 m at outcropping Namurian strata in Ireland (Strachan, 2002), onshore New Zealand (Bull and Cartwright, 2009) and in drilled Cretaceous successions of northern Norway (Shanmugam et al., 1994), to cite three published examples.

Due to their complex internal character, and to their common large scale, submarine landslides are frequently investigated using indirect geophysical methods, i.e., high-resolution seismic or sidescan-sonar data (Hühnerbach and Masson, 2004; Masson et al., 2006). They normally show a wide range of morphologies, which reflect differences in the nature of substrate strata prior to failure, relative inertia of downslope transport, as well as complex interactions between failed strata and the slope morphology (Locat, 2001; Mosher et al., 2004; Lee et al., 2006; Bull et al., 2008). However, one of the principal limitations when using indirect geophysical methods to assess sediment failure relates to the impossibility of correlating, from headwall to toe regions of landslides, the acoustic characteristics of failed strata with their corresponding petrophysical properties. In parallel, outcrop analogues of submarine landslides show diverse lithologies, including coarse-grained sediment, frictional breccia–conglomerate units and local cohesive debris flows with distinct degrees of internal heterogeneity (e.g., Barker et al., 2002; Fleming et al., 2005; Callot et al., 2008a,b; 2009), but exposed successions are either relatively scarce or of limited exposure in the three dimensions (Spence and Tucker, 1997; Payros et al., 1999; Cronin et al., 2000; Graziano, 2001; Lucente and Pini, 2003; Burg et al., 2008). Notably difficult is to relate the relative ratios of failed strata to the thickness of deformed substrate deposits, particularly when strata with similar lithologies are remobilised together during failure. This poses a significant caveat in the interpretation of submarine landslides, as difficulties in recognising the true geometry of their basal surfaces may be responsible for sharp variations in petrophysical properties, as often observed in cored mass-transport deposits from varied continental margins (e.g., Fleming et al., 2005). Therefore, common questions when interpreting industry geophysical data from buried submarine landslide include: (i) what is the true internal structure of the irregular slip planes interpreted on seismic reflection data as comprising the base of landslide strata; (ii) what are the scale relationships between the volume of failed strata and the corresponding thickness of deformed basal strata; and (iii) what would be the impact of deformed basal strata on the sealing competence of submarine landslide successions?

The objectives of this study are to improve understanding of the role of basal strata in mass-transport deposits of submarine settings, and how they affect the downslope transport of carbonate megablocks. We intend to test the hypothesis that there is a relatively consistent ratio of shear plane to mass-transport deposit thickness in submarine settings, a characteristic providing evidence for the critical role of the basal shear planes in the styles of mass-transport processes. This paper starts with a review of the regional geology of SE Crete, followed by a description of the lithology of the investigated units. Previous geological maps published in Fortuin (1977, 1978); Fortuin and Peters (1984); Postma and Drinia (1993), and Postma et al. (1993) have shown most of the studied strata as being part of a Late Miocene (marine) slope systems. Complementing these latter works, a detailed geological map highlighting the position of carbonate megablocks in the palaeoslope is presented, and main collapse styles are documented.

This work shows details of the gravitational collapse styles observed at outcrop, estimating the transporting distances observed for each of these styles. We emphasise the deformation styles of Late Miocene submarine failures. Statistical data on the relationships between failed strata and (deformed) basal shear surfaces are shown, as well as information on the types of structures formed at the base of the palaeoslope when of the principal phase of gravitational collapse. Finally, we discuss the applicability of the acquired data to the interpretation of industry geophysical data. In summary, this work:

(i) documents the styles (and associated landforms) of gravitational collapse observed on a Late Miocene slope in southeast Crete;
(ii) presents new geological interpretation on the role of basal strata in the downslope transport of large megablocks; and
(iii) compares lateral spreading (cf. Lourenço et al., 2006) in the submarine environment with subaerial failures in specific regions of the investigated paleoslope.

2. Materials and methods

Outcrop data were acquired in the Kalogeri–Mirtos–Kalamavka area, NE of Ierapetra, and in the Tertsa–Avri region west of Mirtos (Fig. 1). The approach was to map in great detail any morphological features related to gravitational collapse within the Prina series, Males, Kalamavka, Makrilia and Ammoudhares Formations (Fig. 2). We mapped exposed carbonate blocks and slumped strata with more than 25 m^2 in surface area, together with slumped strata within the Makrilia and Ammoudhares Formations. In total, sedimentological data, outcrop logs, and photomosaics from 72 field sites were used in this work. The geological mapping undertaken was aimed at:

(i) documenting the morphologies of collapsed strata within the Males Formation, Prina series, Kalamavka and Makrilia/Ammoudhares Formations;
(ii) understanding the scales (and relative timings) of collapse features within the investigated palaeoslope; and
(iii) locally, document the characteristic features of basal strata of collapsed megablocks as well as principal structures formed during downslope movement.

According to Fortuin (1978), strata fragmented by gravity gliding in a submarine environment show, in the study area, marked basal deformation features in adjacent marine deposits, which formed the palaeoseafloor. The degree of deformation within basal strata is variable, showing dense fracturing at places. Subaerial collapse usually does not involve any significant deformation of marine strata at the base of megablocks. Only the Males Formation occurs at the base of megablocks involved in subaerial collapse.

Army maps of scale 1:50,000 (Hellenic Mapping and Cadastral Organization) were used as base maps during the work. The relative dating of the investigated units was based on Fortuin (1977, 1978); Meulenkamp (1979); Postma and Drinia (1993); Postma et al. (1993) and Van Hisnbergen and Meleunkamp (2006). The nomenclature of Spence and Tucker (1997) is used throughout this paper. The latter authors introduced the terms *megabreccia* and *megablocks* to define the geometry of limestone-rich breccia strata preferentially deposited on tectonically active slopes. *Megabreccia* comprises a broad term describing all the end products of gravitational collapse on continental margins. Large coherent blocks in failed strata are named *megablocks*, which reflect elastic behaviour. We use this term throughout the paper to define large isolated blocks of boulder conglomerates, carbonate breccias and other slumped strata that were transported downslope in the study area. Accordingly, debris-flow deposits may comprise large boulders but are transported downslope within a disaggregated matrix of reduced shear strength, reflecting plastic behaviour (Spence and Tucker, 1997).

3. Geology of SE Crete

3.1. Pre-Miocene structural evolution

On Crete, basement units of pre-Miocene age include mainly carbonate strata accumulated on a former microcontinent (Apulia or