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Failure mechanisms of Ana Slide from geotechnical evidence, Eivissa Channel, Western Mediterranean Sea

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ABSTRACT

This work deals with the failure mechanisms of Ana Slide in the Eivissa Channel, in between the Iberian Peninsula and the Balearic Islands, under the effects of gas charging and seismic loading. In situ geotechnical tests and sediment cores obtained at the eastern Balearic slope of the Eivissa Channel suggest that the basal failure surface (BFS) developed as a result of subtle contrasting hydro-mechanical properties at the boundary between a fine-grained unit (U6) overlying a methane-charged relatively coarser unit (U7). Past methane seepage is inferred from seismic reflection profiles and high magnetic susceptibility values in sediments from the slide headwall area. Past methane charging is also supported by further seismic reflection data and isotopic analyses of benthic foraminifera published separately. The possibility of failure for different critical failure surfaces has been investigated by using the SAMU-3D slope stability model software taking into account the role of free methane in the development of the landslide. Failure would occur after SAMU-3D if the undrained shear strength of units U6 and U7 is strongly degraded (i.e. 95%). Wheeler's theory suggests that a 9% free gas saturation would be required to reduce the undrained shear strength by 95%. However, the theory of the undrained equilibrium behaviour of gassy sediments for this methane concentration shows that the excess fluid pressure generated by gas exsolution, estimated at 12% of the effective stress, is not high enough to bring the slope to fail. This led us to consider seismic loading as an additional potential failure mechanism despite the lack of historical data (including instrumental records) on seismicity in the Balearic Islands, therefore assuming that the historical period is not necessarily representative of seismic activity further back in time (i.e. when Ana Slide occurred ~61.5 ka ago). Considering current slope conditions, the most critical failure surface obtained by SAMU-3D relates to peak ground accelerations (PGA) of 0.24 g, which relates to magnitude moment Mw = 5 at epicentral distances of 1 km, and 7 ≥ Mw ≥ 5 at epicentral distances ≤ 15 km to Ana Slide. However, no active faults have been identified at so short distance from Ana Slide. Only when shear strength is degraded due to the presence of free methane in units U6 and U7 is considered, the most critical failure surface obtained by SAMU-3D fits with lower magnitude and larger epicentral distances. Consequently, the most plausible hypothesis to explain the occurrence of Ana Slide is the combination of free gas and seismic loading.

1. Introduction

Ana Slide covers 6 km^2 and is located on the eastern Balearic flank of Eivissa Channel (Fig. 1a). This small landslide is aligned with three other landslides (Joan, Nuna and Jersi, Fig. 1b) along the 0°48′E meridian at water depths ranging from 600 m depth at the rim of the shallowest headscarp (Joan Slide) down to 900 m at the lower edge of the deepest landslide toe (Jersi Slide) (Lastras et al., 2004, 2007). The current seafloor expression of Ana Slide ranges from 635 m to 790 m of water depth, with an average slope of 1.6° (Lastras et al., 2004) (Fig. 1c). Previous work based on multibeam bathymetry, backscatter and high-resolution seismic reflection profiles indicated that modest mass transfer accompanied the downslope propagation of the deformation front of Ana Slide, which extensively remoulded the underlying slope sediments without necessarily displacing them too far downslope. Only a slight displacement is observed for most of the sediment in the central and lower sections of the landslide (Lastras et al., 2004). Extensional ridges in the headwall area of Ana Slide correspond to detached subvertical slabs of partially

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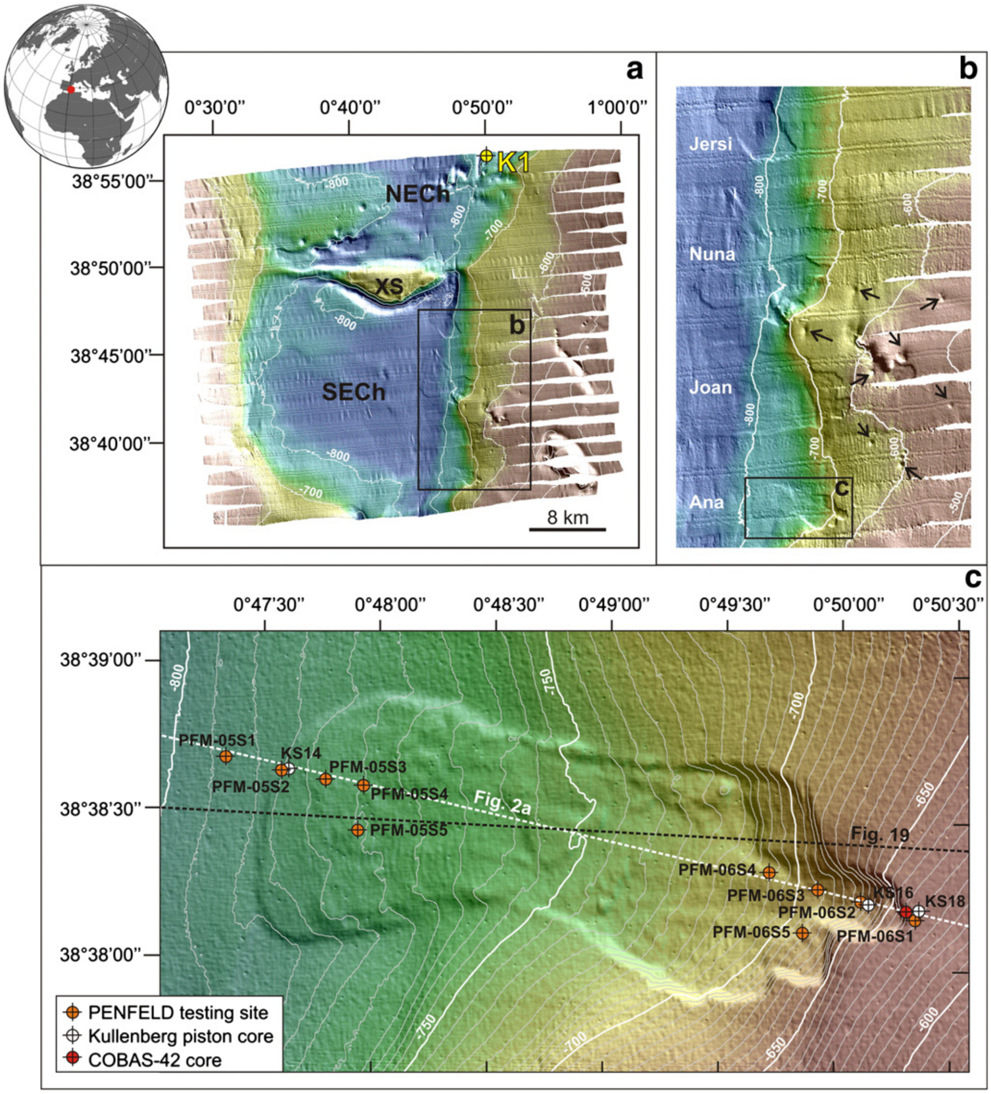

Fig. 1. (a) Shaded relief image of the Eivissa Channel showing the west–east oriented Xàbia Seamount (XS) separating the northern and southern parts of the channel (NECh and SECh, respectively). The study area corresponds to the eastern slope of the southern Eivissa Channel (b box). The position of core K1 (in yellow) from Flores et al. (1997) is also shown. Isobaths (white contours) are every 100 m. (b) Detailed shaded relief image of the eastern slope of the southern Eivissa Channel showing the location of Ana, Joan, Nuna and Jersi landslides from south to north. Large fluid escape structures (pockmarks) are marked by black arrows. Bathymetry in a and b is from Marinada 2002 cruise. (c) Shaded relief image of Ana Slide showing the location of PENFELD CPTU (orange symbols) and Kullenberg cores (white symbols) coring stations during PRISME cruise. Most stations are along the WNW–ESE oriented TOPAS M-3 seismic reflection profile (white dashed line) shown in Fig. 2a. The location of COBAS-42 core (red symbol) and the seismic line reflection profile extracted from a P-Cable 3D cube (black dashed line) (Fig. 19) are also shown. Bathymetry is from CD178 cruise. Isobaths every 5 m.

disturbed sediments, possibly indicating a retrogressive character (Lastras et al., 2006). The observation that the shear planes of Ana, Joan, Nuna and Jersi landslides correspond to the same seismic reflector (Lastras et al., 2004) points to a likely stratigraphic control of slope stability along the eastern slope of the Eivissa Channel and to common causative factors and triggering mechanisms.

Pockmarks near the headwall scarps of Nuna and Ana slides suggest that fluid escape processes took place in the vicinity of the slides (Lastras et al., 2006, 2007). Fluid escape structures of the Balearic Promontory have been described as extrusion features by gas of thermogenic origin related to Plio-Quaternary submarine volcanism and faulting (Acosta et al., 2001a, b; Maillard and Mauffret, in press). Seismic data acquired across Ana Slide (see Fig. 2 in Berndt et al., 2012) show high amplitude anomalies below the failed sediment mass, which are attributed to free gas, even though the polarity of these reflections is ambiguous (Berndt et al., 2012). The presence of methane in the recent past has been also inferred from δ^{13}C analyses on benthic foraminifera *Hyalinea balthica* and *Uvigerina peregrina* assemblages from sediment samples extracted from a sediment core recovered at Ana's headwall (Panieri et al., 2012).

The role of gas charging in slope instability is generally related to gas exsolution and overpressure formation during sea-level falls. Sobkowicz and Morgenstern (1984) consider that if equilibrium conditions prevail during undrained unloading (equivalent to sea-level falls) of gassy sediments (i.e. sediments containing large gas bubbles), the pore pressures remain close to the liquid/gas saturation pressure and effective stresses are reduced significantly. Pore pressure response due to changes in total stress such as sea-level falls generates gas exsolution and subsequent loss of effective stress, which leads to a reduction in the strength of the sediment. Other models developed to predict the behaviour of gassy sediments assume that the water phase is continuous, thus remaining valid the principle of effective stress (Wheeler, 1988 and Grozic et al., 2005). According to Wheeler (1988), a lower bound for the undrained shear strength is defined during undrained failure, which allows quantifying the degree of undrained shear strength degradation due to the presence of gas.