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Repeated slope failure linked to fluid migration: The Ana submarine landslide complex, Eivissa Channel, Western Mediterranean Sea

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ABSTRACT

Submarine slope failures are a well-known geohazard. They are able to destroy seafloor installations along their path and by generating tsunamis they may threaten coastal infrastructures. While the mechanisms involved in submarine landslide generation remain poorly known, there are observations that slope stability can be reduced in the presence of free gas. Here, we present new high-resolution 3D seismic data from the Eivissa Channel between the Iberian Penninsula and the Balearic Promontory in the Western Mediterranean Sea. The data reveal slope stability reduction in this area at least since mid-Quaternary times, and an intimate relationship between fluid migration and slope stability. We show that two landslides, i.e. pre-Ana Slide and Ana Slide, occurred at almost the same location above an erosional channel in the Messinian unconformity. There is seismic evidence that fluids including gas are migrating upwards through this erosional surface and that they charge sedimentary layers at the base of the Ana Slide possibly reducing its strength and predisposing it to failure. Our data show in unprecedented detail the ways in which the presence of gas influences slope stability. The findings illustrate the importance of including high-resolution 3D seismic data in slope stability and tsunami risk assessments to identify shallow gas distribution as one of the main controls on slope stability in gas prone areas.

1. Introduction

Submarine landsliding is a widespread geological phenomenon that shapes submarine slopes on continental margins, ocean islands and seamounts. Some of these landslides involve several thousand cubic kilometres of material that move in a short period of time (Bull et al., 2009; Canals et al., 2004). Slope failures occurring on sediment covered continental margins have been the subject of significant research efforts over the past decades as hydrocarbon exploration moves into deeper waters where landslides threaten submarine installations, and because studies of salt marsh, river estuary, and lake deposits surrounding the northeast Atlantic show that submarine landslides can cause significant tsunamis that endanger coastal populations (Assier-Rzadkiewicz et al., 2000; Bondevik et al., 2005; Harbitz, 1992; Lopez-Venegas et al., 2008; ten Brink et al., 2009; Watts et al., 2003).

The geological processes that lead to unstable slopes are still not fully understood. The most detailed investigation of any submarine landslide, i.e. the Storegga Slide off mid-Norway, concluded that the particular sequence of hemipelagic deposition and glacial debris flows led to overpressures that make this glaciated continental margin inherently unstable (Berg et al., 2005; Bryn et al., 2005; Kvalstad et al., 2005a, 2005b), and that the trigger of this particular landslide must have been an earthquake of M > 7 (Løvholt et al., 2005). However, the spatial relationship of a major gas reservoir and the most deeply incised part of the landslide could also suggest that upwards gas migration played a role in the destabilisation of the slope (Bünz et al., 2005).

Unfortunately, the findings from the Storegga Slide area cannot be generalised for the geological situation away from the influence of glacial processes, where large submarine landslides occur on continental margins in areas of gentle seafloor gradient, e.g. the margins of NW Africa (Henrich et al., 2008; von Rad et al., 1982; Wynn et al., 2000), of the east coast off the US (Dugan and Flemings, 2000, 2002) and in the Gulf of Mexico (Flemings et al., 2008). For these landslides other destabilising mechanisms have been proposed such as overpressuring of the toe of the slopes due to lateral fluid migration from major deposition centres to the distal parts of the continental margin (Dugan and Flemings, 2002). As a result of IODP Expedition 308 to the Gulf of Mexico, a flow-focusing model was produced showing how sedimentation, overpressure, fluid flow, and deformation can be coupled in a passive margin setting and how extremely rapid deposition of fine-

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grained sediment might lead to a rapid build-up of pore pressure in excess of hydrostatic (overpressure), under-consolidation, and finally sedimentary mass wasting (Flemings et al., 2008).

The Mediterranean Sea is a largely land-locked basin where a variety of tectonic and sedimentary environments co-exist in a relatively small area. Here submarine landslides of different sizes and ages are widespread. However, there is no obvious correlation of landslide abundance with tectonic activity or with zones of high sediment accumulation (Camerlenghi et al., 2009). This reinforces the view that it is a combination of geologically driven pre-conditioning factors that control conditions of continental slope instability in the submarine environment (Canals et al., 2004; Lee, 2009; Sultan et al., 2004).

The landslides in the Eivissa Channel at the southern termination of the Valencia Trough (Fig. 1a) lend themselves to the study of the general processes of submarine slope instability as they occur in a low seismicity, rifted continental margin setting characterised by low rates of carbonate-dominated sediment accumulation influenced by bottom currents (Alonso et al., 1988; Canals and Ballesteros, 1997; Lastras et al., 2004). The structure of the submarine landslides in the Eivissa Channel is relatively simple compared to the large multi-phase landslides off Norway or NW Africa, and the run-out length of less than 10 km facilitates complete surveying. A bathymetric survey conducted in 1995 showed that there are at least four landslides originating on the eastern slope (i.e. the Balearic slope) of the channel and running out to the west, named Jersi, Nuna, Joan and Ana slides from north to south after Lastras et al. (2004) (Fig. 1b). High-resolution sub-bottom profiling yielded volumes of less than 0.4 km^3 for each of these landslides (Lastras et al., 2004) and MAK1 side scan sonar data showed translational ridges in the central part of the landslides and compressional ridges in the accumulation zone. There are pockmarks at water depths between 400 and 700 m, which are similar to the water depth at the headwalls of the landslides. A sediment core reaching below the glide plane within the Ana Slide headwall area sampled warm foraminifera fauna of MIS 5 that may be considered the oldest possible age of the Ana Slide. Based on dating of overlying sediments and sequence stratigraphic considerations Cattaneo et al. (2011) proposed a possible age of 60,000 years.

In 2006 we collected a cube of high-resolution 3D seismic data to investigate the processes that lead to slope failure in this area focusing on Ana Slide, the southernmost of the landslides discovered on the eastern slope of the Eivissa Channel. The first objective of this work was to reconstruct the history of slope instability in the area of the Ana Slide. The second objective was assessing the role of different geological processes such as fluid migration, structural deformation and sedimentation history in predisposing the slope to fail and to constrain possible triggers.

2. Method

2.1. P-Cable seismic data

The high-resolution 3D seismic data of this survey (Cruise CD178) were acquired using the RRS Charles Darwin of the National Environment Research Council (NERC) and the P-Cable 3D acquisition system of the National Oceanographic Centre, Southampton (Perez-Garcia et al., 2011). The P-Cable consists of a cross wire (P-wire) extending perpendicularly to the ship's steaming direction. This wire is held in place by paravanes attached to both ends of the wire and towed by the ship. In the normal configuration this system consists of twelve 30 m-long, single-channel Teledyne Instruments analogue streamers, which are connected to the P-wire and towed in line with the ship's movement.

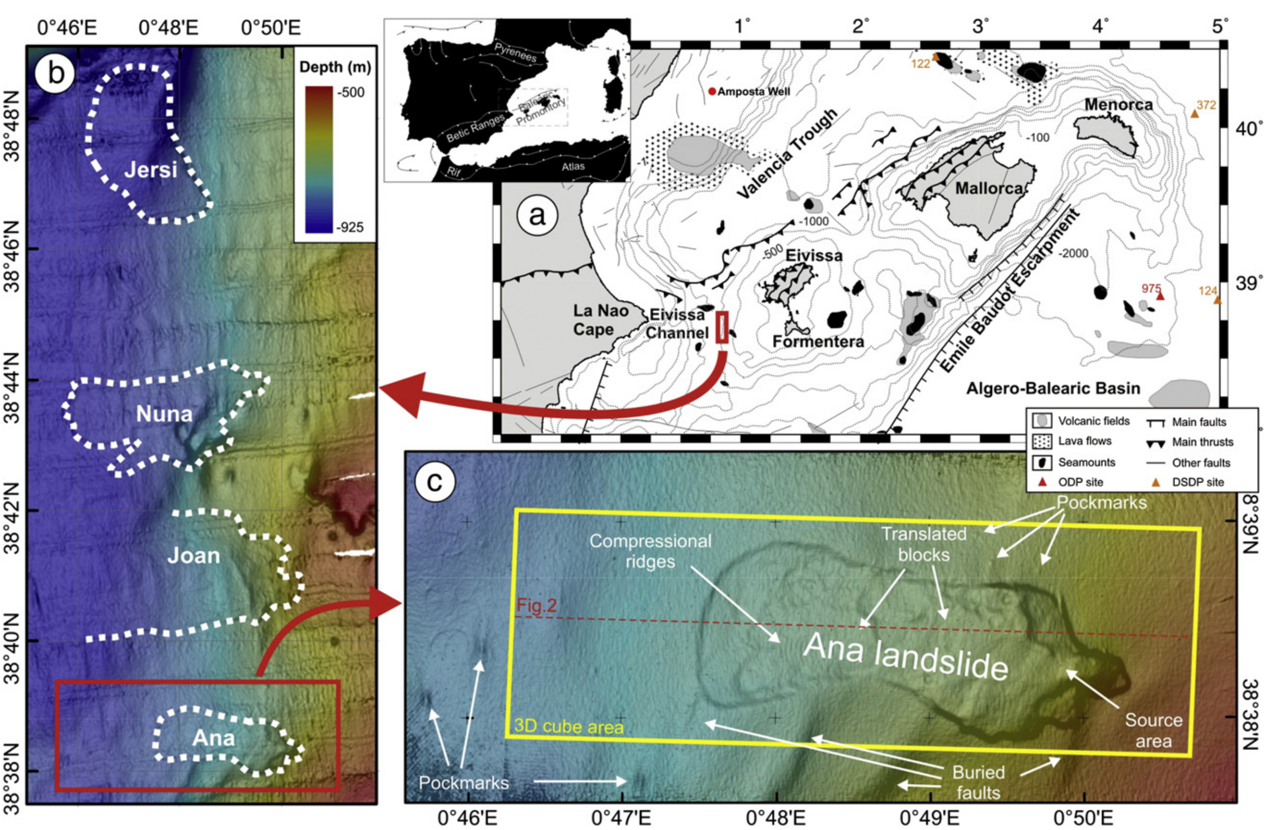

Fig. 1. a: Geological compilation for the western Mediterranean showing the main tectonic structures (adapted from Camerlenghi et al., 2009). Main geological structures of the Balearic Promontory and surrounding areas (Acosta et al., 2002, 2004; Camerlenghi et al., 2009; Maillard and Mauffret, 1999; Mauffret et al., 2004; Roca and Desegaulx, 1992). b: Relative position of the surface-near submarine landslides in the Eivissa Channel (after Lastras et al., 2004). c: New bathymetry data collected during the CD178 cruise showing the detailed bathymetric expression of the Ana Slide. b + c: illumination with the dip map.