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Slope destabilization during the Messinian Salinity Crisis

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ABSTRACT

During the Messinian Salinity Crisis, ~6 Myr ago, deep canyons were incised when a huge sea-level drawdown of ~1.5 km affected the Mediterranean Sea. Nearly contemporaneously, more than 2 km of evaporites accumulated in the basin. This event was the consequence of a complex interaction of tectonic movements and global sea-level variation associated with climatic evolution. This unusual event ended with the reflooding of the Mediterranean area. In this paper, using seismic line interpretation, we show that several landslides occurred in various parts of the Mediterranean Basin during this crisis. Three of these landslides are well preserved, and their dynamics were analyzed. Modeling of the slope stability demonstrates that these landslides may have been due to (i) the relief created by the deep erosion, and/or (ii) the reflooding, which triggered a pore pressure increase. The relatively small run-out distances of the three landslides suggest propagation in a submarine environment and triggering by sea-level rise.

1. Introduction

Landsliding is one of the most catastrophic phenomena that affect planetary surfaces and is one of the most efficient processes for modifying the surface morphology. Landslides are the consequence of complex interactions between geological and climatic phenomena. The primary factors that influence the occurrence of landslides are earthquakes (Keefer, 1994), oversteepening of slopes by incision, glacial loading, storm-wave loading (Locat and Lee, 2002), rapid accumulation of sedimentary deposits or weak volcanic debris (Mitchell and Lofi, 2008), volcanic island growth (Hampton et al., 1996), gas hydrate release destabilization (Nisbet and Piper, 1998) and precipitation (Crozier, 2010). From a physical point of view, the processes that play a major role in slope destabilization are the mechanical properties of the rock (cohesion and friction angle), stress increase and pore pressure variation (Locat and Lee, 2002; Kilburn and Petley, 2003; Bigot-Cormier and Montgomery, 2007). The physical laws that allow us to predict the occurrence, geometries and dynamics of landslides are still a subject of debate (Helmstetter et al., 2004; Staron and Lajeunesse, 2009).

We investigated the margin morphology of the Mediterranean Basin. The more spectacular features in this area are the surfaces and deposits of Messinian age triggered by significant sea-level lowering. Numerous changes occurred in association with this event, such as deep subaerial erosion (Barber, 1981; Clauzon, 1982) and deposition of thick sedimentary sequences (Montadert et al., 1978; Rouchy and Caruso, 2006). We focused our investigation on (i) the Gulf of Lion, (ii) the Nile delta and (iii) the Alboran Sea (Fig. 1A) and observed that several landslides occurred during Messinian time. The Messinian crisis event triggered new geologic conditions that favored the development of landslides. A fluvial erosional crisis (Clauzon, 1982; Griffin, 1999; Willett et al., 2006; Bache et al., 2009) and a salinity crisis (Hsu et al., 1977) during the Messinian time have been identified, and seismic lines allowed us to demonstrate that several landslides also occurred during the same period in the Mediterranean area. In this study, we (i) describe these landslides and (ii) explain the cause and the dynamics of these landslides using numerical modeling. The aim of this study was not to provide a seminal contribution to the understanding of landslide physics, but to use landslide analysis to improve our understanding of the Messinian Salinity Crisis.

2. Geologic setting

At the end of the Miocene, the Messinian in the Mediterranean area was characterized by a restriction of water flux between the Atlantic Ocean and the Mediterranean area by a combination of tectonic activity and sea-level variations in the global ocean. This restriction led to the partial isolation of the Mediterranean Sea 5.96 Myr ago (Krijgsman et al., 1999). As a consequence, a dramatic Mediterranean sea-level drawdown of more than 1000 m occurred (Le Pichon et al., 1971; Hsu et al., 1977) 5.6 Myr ago (Krijgsman et al., 1999). The amplitude and precise magnitude of local sea-level fall during this period are still a subject of debate (Gargani and Rigollet, 2007). Associated with this spectacular local sea-level drop, deep canyons (>1000 m deep) were incised all around the Mediterranean Basin (Barber, 1981; Clauzon, 1982;

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Lofi et al., 2005; Maillard et al., 2006; Bertoni and Cartwright, 2007; Cornée et al., 2008) and thick evaporite sequences (>1500 m) were deposited at the centers of the basins (Montadert et al., 1978; Meijer and Krijgsman, 2005; Rouchy and Caruso, 2006). These evaporites are the reason why this event is often referred to as the Messinian Salinity Crisis (MSC). Contemporaneously with the deposition of the evaporites, the Mediterranean sea-level may have fluctuated (Gargani and Rigollet, 2007; Gargani et al., 2008) and/or risen slowly (Bache et al., 2009). The MSC ended when a reflooding occurred at 5.33 Myr in the Gibraltar area (Blanc, 2002; Loget et al., 2005; Garcia-Castellanos et al., 2009). Then, Pliocene sediments filled in the Messinian canyons (Clauzon et al., 2005).

Depending on the pre-existing morphology of the sub-basins, the general scenario of the crisis triggered a specific evolution in each sub-basin. Several studies (Blanc, 2002; Gargani and Rigollet, 2007; Gargani et al., 2010) have indicated that the sea-level lowering was deeper in the eastern Mediterranean Basin than in the western basin. The Sicily sill isolated the eastern basin from the western basin during part of the crisis (Blanc, 2002). Numerous Messinian canyons have been observed along the Egyptian margin (Gargani et al., 2010), the Levant margin (Druckman et al., 1995; Bertoni and Cartwright, 2007) and the Lybian margin. The deeply incised Nile River (north eastern Africa) did not exist prior to the Messinian. It is believed that the drainage of southern Egypt before the MSC was dominated by a river (Qena River) that drained southward east of the present Nile River (Issawi and McCauley, 1992; Goudie, 2005). The primary Messinian deposits of the Nile valley are the Qawasim formation, the Rosetta anhydrite and the Abu Madi Formation (Rizzini et al., 1978). These formations overlie earlier primarily marine Miocene sediments (Griffin, 1999).

In the western Mediterranean Basin, deep incisions of ~1500 m associated with the Messinian sea-level lowering were also observed along the Ebro margin (Urgeles et al., 2010), in the Gulf of Lion (Lofi et al., 2005) and in the Valencia basin (Maillard et al., 2006). Basically, the western Mediterranean Basin formed since ~30 Myr (Burrus and Audebert, 1990) by the eastward roll-back of the Apennines subduction front. In the Gulf of Lion, Messinian incision affected marine Miocene sediments.

Another area between the western basin and the Atlantic Ocean was also investigated owing to its fundamental location during the Messinian crisis: the Alboran Sea. The Alboran Sea is 150 km wide and 350 km long, and is bounded by the Gibraltar Arc and Spanish Betic Mountains on the north and the Moroccan Rif Mountains on the south (Estrada et al., 2011). The basement of the Alboran Basin is composed primarily of metamorphic and volcanic rocks. The sediment fillings of the Alboran Basin are composed of Early Miocene to Quaternary marine deposits (Estrada et al., 2011). The marine sediments predating the crisis are composed of clays and silty clays interbedded with minor marly intervals (Serravalian–Tortonian) or by clays and silty clays interbedded with sandstones of Tortonian age (Jurado and Comas, 1992).

Even if the paleogeography and the paleotopography are not identical in this three cases (Egyptian margin, Gulf of Lion and Alboran Sea), all of these area were affected by similar geomorphological events during the Messinian: sea-level lowering, erosion, reflooding and load-induced flexure. The evolution of the Mediterranean Basin during the MSC may have triggered unique conditions amenable to the study slope destabilization on a large scale. We documented and analyzed several Messinian landslides that were not totally disaggregated during their propagation, although several completely disaggregated landslides were also observed.

3. New seismic observations

Using a set of seismic lines in the Gulf of Lion, the Nile delta and the Alboran Sea, we identified several seismic bodies sandwiched between the Messinian erosional surface and the youngest Pliocene sediments (Fig. 1). These seismic bodies were situated such that they were subaerially exposed during the MSC and reflooded at the end of the crisis.

Two seismic facies were observed within these seismic bodies. The first facies is characterized by seismic chaos, whereas the second facies is characterized by low amplitude, relatively continuous reflectors (Figs. 2 and 3). We interpret these facies as landslides composed of sediments that were completely disaggregated in the first case and sediments that were only displaced in the second case.

No chaotic seismic bodies were analyzed, due to the difficulty of characterizing their initial morphologies. In this study, we analyzed only the landslides in which a portion of their initial shape was conserved. These landslides are located landward of the Messinian detrital deposits and evaporites, directly overlying pre-Messinian sediments affected by the Messinian erosional surface. The distribution suggests that the genesis of the landslides is not linked to the Messinian deposits. Nevertheless, the presence of a wave-cut sedimentary unconformity along the upper surface of the Messinian detrital deposits (Bache et al., 2009), which represents the reworking of previous topographies, does not disallow the presence of landslides linked with evaporites or detrital deposits.

The landslide in the Gulf of Lion (Fig. 1B) is ~1000 m wide, ~300 m long and ~300 m thick. This landslide occurred on the sideslope of a canyon incised during the MSC and affected stratified sediments of Miocene age (Bache et al., 2009). This landslide has a mass of approximately ~216 $\times$ 10^9 kg. The landslide observed in the Nile delta (Figs. 1D and 3) occurred on the sideslope of a deep canyon. Miocene marine sediments (pre-Messinian) were impacted by this landslide. This landslide is ~300 m thick, ~400 m long and ~1200 m wide (~3.45 $\times$ 10^{11} kg). The valleys where these landslides occurred are of Messinian age and were incised after the drawdown of the Mediterranean Sea. Nevertheless, a few of the landslides of Messinian age occurred outside of Messinian valleys, as in the Alboran Sea (Figs. 1C and 2). In one such case, the landslide is ~150 m thick and ~400 m long (width undetermined).

The landslides presented in Figs. 1, 2 and 3 apparently were not totally disaggregated and have an apparent final slope of ~15°. Nevertheless, even these landslide masses were not totally disaggregated, it is clear that their initial shapes were modified by their sliding and spreading. As a result, large ranges in their thicknesses and initial slope gradients must be considered. The assumption of a maximum thickness variation of ~100 m allowed us to estimate an initial thickness *H* of between 300 and 400 m. The assumption of a landslide displacement of ~500 m along the sliding path identified in the seismic lines allowed us to estimate an approximate initial slope gradient β ranging between 15° and 40°.

4. Modeling method

4.1. Stability analysis modeling

To analyze the causes that triggered the Messinian landslides, a basic 2D model was used. Owing to the lack of information constraining the exact material properties and boundary conditions, this analysis was performed only to evaluate the essential parameters involved in the geomorphologic evolution of the Mediterranean during the Messinian. The potential influence of three processes was explored: (1) pore pressure increase, (2) slope change, and (3) ground acceleration. Each of these processes may be associated with specific geologic phenomena that will be discussed later.

Two geometries of the landslides were analyzed to test the role of the landslide geometry in the slope stability. The first geometry (Fig. 4A) was based on the Cullman wedge model (Bigot-Cormier and Montgomery, 2007). In such a model, a balance is essentially achieved between the weight of the expected landslide and the resisting forces generated by the rock. The prefailure resisting shear stress along the slip surface is given by $\tau_c = \sigma_n \tan\phi + C$, where σ_n is the normal stress, ϕ is the friction angle of the slope-forming material and *C* is the