Altered volcanic deposits as basal failure surfaces of submarine landslides

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ABSTRACT
One of the main concerns regarding the development of submarine landslides is the role played by weak layers in the failure process and, in particular, their impact in terms of volume, shape and evolution of mass movements. In the present study we identified a weak layer in the eastern margin of the Corsica Trough (northern Tyrrhenian Sea) that formed the basal failure surface of the Pianosa Slump at 42–50 ka. This layer is characterized by high water content, high plasticity, high compressibility, and post-peak strain softening behavior (i.e., strength loss with increasing strain). These specific mechanical and sedimentological properties seem to be related to the presence of analcime zeolites with a concentration of 2–4% in the muddy sediment. Zeolites commonly form by the alteration of volcanic rocks and were deposited on the slope during a sea level low-stand. The influence of the zeolitic layer on slope instability was tested numerically using an elastic-perfectly plastic model that exhibits strain softening. Modeling results show that erosion at the foot of the slope could lead to enough strain to reduce the shear strength of the zeolitic layer and lead to slip in this layer. We conclude that the strain softening behavior of muddy zeolitic sediment plays an important role in predisposing submarine landslides on continental slopes.

INTRODUCTION
The large size of submarine landslides compared to their terrestrial counterparts is related, among other factors, to the presence of extended weak layers within marine sediments accumulated along continental slopes (Puzrin et al., 2016). Locat et al. (2014) pointed out that weak layers may be inherited from the original properties of sediment or induced by external factors. Strain softening behavior is widely considered as a major factor in the development of large-scale progressive failure, as demonstrated for the Storegga slide (Dey et al., 2016). Understanding the mechanical and sedimentological properties of weak layers is the key to identifying the potential failure surface of submarine landslides and to modeling their lateral propagation (Puzrin et al., 2016). In this work, we suggest that zeolites, a product of volcanic rock alteration (Mumption, 1999), influence the sedimentological and geotechnical properties of fine marine sediment and contribute to the development of slope failure. This finding has potentially broad impact since many regions in the world contain abundant volcanic material that can be a potential source of zeolites (Fig. 1).

A ZEOLITIC WEAK LAYER
The Pliocene–Quaternary sedimentary deposits along the Pianosa Ridge (northern Tyrrhenian Sea) are composed of muddy contours that were affected by multiple mass-wasting events (Fig. 2A; Miramontes et al., 2016, 2018). The most recent of them, called the Pianosa Slump (PS), occurred between 42 and 50 ka in a convex-shaped contourite, flanked by zones of focused erosion (moats) at the foot of the slope, where slopes reach 10–16° (Fig. 2A; Miramontes et al., 2018). The timing of the Pianosa Slump formation coincides with a period of sea-level fall (between 52 and 48 k.y. B.P.), during which erosion at the moats was enhanced due to an increase in bottom-current intensity (Miramontes et al., 2016).

The PS headwall is located at 500–670 m water depth and the scar is currently covered by 20 m of sediment (Figs. 2B and 2C). Multi-channel high resolution mini GI gun (50–250 Hz) and sub-bottom profiler (SBP; 1800–5300 Hz) seismic reflection data, acquired during the PRISME2 cruise in 2013 (R/V L’Atalante; https://doi.org/10.17600/13010050), show that the basal failure surface of the PS follows a regional stratigraphic horizon marked on seismic profiles by high-amplitude reflections (Figs. 2B and 2C). At the time of failure, this horizon was at ~35 m below the seafloor (mbsf; Figs. 2B and 2C), and its age has been estimated at ca. 150 ka based on the chronology proposed by Miramontes et al. (2016). In three Calypso piston cores (CS11, CS12 and CS21), collected in undisturbed areas during the PRISME3 cruise in 2013 (R/V Pourquoi pas?; https://doi.org/10.17600/13030060) (Fig. 2A), this horizon corresponds to a 2–4-m-thick layer. X-ray diffraction analyses on 12 samples from cores CS12, CS17, and CS21 revealed that, in contrast to the adjacent sediment, this particular layer contains analcime zeolitic minerals in a mass concentration of 2–4 wt% (Table DR1 in the GSA Data Repository). This difference in bulk mineralogy is not associated with a significantly different clay mineralogical composition (Table DR2) or grain size (Fig. DR3). The scanning electron microscope (SEM) image of a zeolitic sediment thin section shows that zeolites are uniformly distributed in the sediment and have a typical diameter of ~50–100 µm (Fig. 3A). Although deeply buried, this particular sediment has a water content as high as 89 wt%, similar to that of surface sediment values (Fig. 3B). The sediment water content (related to sediment porosity) and zeolite content tend to be linearly correlated (Table DR4, Fig. DR5). The liquid limits obtained by the fall cone method are very high (up to 100%) for zeolitic sediments compared to non-zeolitic sediments that are always below 77% (Fig. DR6). Therefore, despite its high water content, the zeolitic sediment is not in a state of potential flow. Plasticity indices are also high for the zeolitic sediment (50–70), twice the values obtained from the adjacent sediment (Fig. 3B). Based on oedometer test data, all the sediments are normally consolidated, but those containing zeolites exhibit a higher (post-gross yield) compressibility (Fig. DR7).

In order to determine the strength properties of the sediments, we performed seven consolidated anisotropic undrained compression (CAUC) triaxial tests on samples from cores CS12 and CS21 (Table DR8, Fig. DR9). These tests revealed that the undrained shear strength of the zeolitic sediment reaches a peak value at lower strains than the adjacent sediment: at 2% of axial strain, in contrast to 8% for the non-zeolitic sediment. Moreover, the zeolitic sediment displays a more pronounced strain softening; its...
undrained shear strength is reduced by 33% at 15% strain (Fig. 4).

SLOPE STABILITY MODELING

The influence of the strain-softening zeolitic layer on slope instability is simulated with the commercial software Plaxis 2D (https://www.plaxis.com/product/plaxis-2d/, Brinkgreve et al., 2012). The model geometry is divided into 12 sedimentary layers, 5 m thick, except for the zeolitic layer that is 3 m thick (at 35–38 mbsf) and the deepest layer that is 7 m thick (at 53–60 mbsf) (Fig. 5A; Table DR10). The initial slope angle in the zone of the moat is 10.5° (Fig. 5A). The sediment layers are modeled as a Mohr-Coulomb material. The zeolitic layer is also modeled as an elastic—perfectly plastic material, but an approximated strain-softening approach is used to simulate the post-peak shear strength loss by applying the method proposed by Lobbestael et al. (2013), based on Lo and Lee (1973) and Potts et al. (1990). The approach consists of tracking the plastic strains and reducing the shear strength accordingly, using the stress-strain curve obtained from the CAUC triaxial test carried out on a zeolitic sediment sample (Fig. 4). The zeolitic layer is laterally divided into small sections (50 m long and 3 m high) to locally reduce the strength parameters in successive steps. In order to reproduce the observed slope geometry, we simulated a total erosion of 5 m at the moat by removing 1 m of sediment in five successive steps. The erosion is maximal at the central part of the moat, decreasing to zero over a distance of 200 m upslope and downslope of the central part of the moat (Fig. 5A). We performed the slope stability calculation under undrained conditions because the development of catastrophic failure, which is the most critical scenario, is expected to occur very rapidly and will thus mobilize the undrained parameters of the sediment (Puzrin et al., 2016).

The slope stability analysis performed before the erosion phases provides a factor of safety (FOS) of 1.15 with a shallow potential failure surface (Fig. 5A). After the first erosion phase and the induced strain softening within the zeolitic layer, the failure surface is deeper, crossing the particular layer (Fig. 5B). Increasing erosion at the foot of the slope induces a lengthening of the shear zone within the zeolitic layer (Figs. DR12 and DR13). According to the numerical model results, a 5 m erosion would trigger the collapse of the slope (i.e., FOS < 1).

DISCUSSION AND CONCLUSION

Role of Zeolites in Slope Stability

The basal shear zone of the Pianosa Slump formed in a zeolitic layer (with high water content, plasticity, and compressibility) that tends to readily soften when sheared undrained. The compressibility of clays depends not only on their mechanical properties, but also on the soil physico-chemical properties (Bolt, 1956). The diffuse double layer (DDL) theory of Gouy-Chapman explains the ionic distribution around clay minerals, which generally are negatively charged (Bolt, 1956). According to this theory, the DDL thickens with a reduction in the ionic concentration and/or in the ionic valence, resulting in an increase of the sediment porosity (Bolt, 1956). Zeolites are widely used in agriculture and industry applications due to their high cation exchange capacities, that can be higher than in clays (Mumpton, 1999). Zeolite particles in marine fine-grained sediment could attract more cations than the clay particles, resulting...
in a decrease of the cation concentration in the vicinity of clays. Consequently, according to the Gouy-Chapman theory and Bolt (1956), the DDL of clay particles and the repulsive forces would increase, generating a weak sediment structure with higher porosity and compressibility (Fig. DR11). Because zeolites are uniformly distributed in the failed sediment layer (Fig. 3A), this process could affect the whole zeolitic layer.

The results of the slope stability analysis show that erosion in the moat, located at the foot of the slope, can generate enough strain to substantially reduce the strength of the zeolitic layer due to its strain-softening behavior (Fig. 5). Simulations also show that successive erosion phases generate a progressive lengthening of the initial softened zone (Fig. DR12). The predicted failure surface appears to develop along the softened zone but does not extend upslope as much as is observed for the PS (Fig. 5). This is attributable to model limitations in simulating stress transmission from a softened zone to the neighboring undisturbed sediment, as is expected to occur under existing or additional external forces in catastrophic or progressive failure, respectively (Puzrin and Germanovich, 2005).

Our findings concerning the mechanism of weak layer formation in fine-grained marine sediment with altered volcanic deposits could apply to all continental margins close to zones with volcanic material (Fig. 1). The strength of a zeolitic layer could be reduced by erosion, as in the Pianosa Ridge, but it could be also reduced by other external processes such as seismic loading, overloading and steepening.

**Origin and Distribution of Zeolites in Marine Sediments**

The origin of zeolites in the Pianosa Ridge is probably not linked to the burial metamorphism of volcanic ashes because it was at only 35 mbsf at the time of the mass failure, and this type of alteration usually happens hundreds of meters below the surface (Wiemer and Kopf, 2015). Moreover, in situ formation of zeolites in the marine sediment is unlikely due to the lack of sediment with altered volcanic deposits could apply to all continental margins close to zones with volcanic material (Fig. 1). The strength of a zeolitic layer could be reduced by erosion, as in the Pianosa Ridge, but it could be also reduced by other external processes such as seismic loading, overloading and steepening.

**Figure 3. A:** Chemical composition map, obtained with a scanning electron microscope, of a zeolitic sediment thin section (core CS12, at 21.9–22.0 m) showing the zeolites in pink, and typical spectra of zeolites. Note that zeolites are uniformly distributed in the sediment, with a typical diameter of ~50–100 µm. cps/eV—counts per second per electron volt. **B:** Water content (w) of the three sediment cores that sampled the zeolitic sediment layer, and plasticity index (PI) of cores CS21 and CS12.

**Figure 4.** Undrained shear strength obtained from consolidated anisotropic undrained compression (CAUC) triaxial tests performed on one zeolitic sediment sample from core CS21 (purple line, at 21.31–21.47 mbsf) and one non-zeolitic sediment sample from core CS12 (red line, at 26.28–26.42 mbsf). The mean effective stress after saturation and consolidation applied in each test was 127 kPa.

**Figure 5.** Total deviatoric strain after sediment consolidation (A) and after the strength reduction in the zeolitic layer caused by a 4 m erosion in the moat (B). The lower plots show the critical failure surface at stages A and B. The observed failure surface of the Pianosa Slump (PS) is marked with a dashed white line. FOS—factor of safety.
The presence of zeolites has been widely documented in volcanic settings; for example, in the circum-Pacific arc (Michels et al., 2014), in the Antilles volcanic arc (Jolly et al., 2001), in the Mediterranean Sea (Altran et al., 2013), and in volcanic islands such as the Canary Islands (Donoghue et al., 2008), Cape Verde (Barker et al., 2009), Hawaii (Morgan and Clague, 2003), or Reunion (Bachelery et al., 2003). The formation of sediment layers rich in zeolites can be extended in time and is not only restricted to the period of zeolite mineral formation, since the minerals can be stockpiled onshore or on the continental shelf and later transported to the continental slope. Detecting the presence of zeolites in marine sediments may help to understand the pre-conditioning conditions of submarine landslides on continental margins close to volcanic zones.

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