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# Discovery of a gliding salt-detached megaslide, Calabria, Ionian Sea, Italy

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[1] Integrating seismic reflection profiles, well logs, and field evidence with GPS velocities from a network installed in Calabria, southern Italy, we have discovered that the Crotone basin is gliding toward the Ionian Sea over a buried viscous salt layer. This previously unknown megaslide (~1000 km$^2$) is characterized by an onshore updip extensional domain and an offshore downdip toe-thrust rim. The GPS velocity from the Crotone station is significantly higher than velocities from other stations in the region and differently oriented. We ascribe at least part of the anomalous GPS velocity from the Crotone station to the seaward motion of the megaslide or part of it. From the GPS velocity and other evidence, we obtain a viscosity of the buried salt layer within the known range of rock salt viscosity in nature. **Citation:** Minelli, L., A. Billi, C. Faccenna, A. Gervasi, I. Guerra, B. Orecchio, and G. Speranza (2013), Discovery of a gliding salt-detached megaslide, Calabria, Ionian Sea, Italy, *Geophys. Res. Lett.*, *40*, 4220–4224, doi:10.1002/grl.50818.

## 1. Introduction

[2] The study of salt-related structures and of rock salt properties (deformation rate and viscosity) is relevant for different applications, including hydrocarbon exploration and safe storage of hazardous wastes [*Jackson and Talbot*, 1986; *Rowan and Vendeville*, 2006; *Hudec and Jackson*, 2007; *Hou et al*., 2010; *Jackson*, 2012]. Additionally, where salt tectonics occur on land [e.g., *Hafid et al*., 2010], it may pose serious hazard to civil works and constructions. Understanding salt tectonics processes and measuring the related deformation rates are hence crucial both for industrial and for civil reasons. However, direct measurements of salt tectonics rates in nature are still very limited and principally carried out on exposed salt diapirs and cascades [*Weinberg*, 1993; *Weinberger et al*., 2006; *Aftabi et al*., 2010]. No direct measurements of salt tectonics rates exist, for instance, on large salt-detached slides.

[3] Below, we report on the discovery of an actively gliding salt-detached megaslide in the Crotone basin, Calabria, southern Italy (Figure 1). Coupling geological and geophysical data, we constrain its geometry and structure. The novel aspect of our analysis is that we are able to determine the slide seaward gliding rate through GPS measurements. We conclude deriving the viscosity of rock salt from this rate and other evidence.

## 2. Methods and Results

[4] In 2006, within the framework of the Calabrian Arc Project funded by the National Science Foundation (http://geomorph.ldeo.columbia.edu/calarco/), eight continuous GPS stations were installed along a NW-SE transect through northern Calabria [*D'Agostino et al*., 2011] (Figure 1). We analyzed 3 years of GPS data (Figure 1b and Table S1 in the supporting information) using the GAMIT/GLOBK software [*Herring*, 2005] and standard processing procedures [*Blewitt*, 1998; *Serpelloni et al*., 2005]. Consistently with previous studies [*D'Agostino et al*., 2011] (Figures 1a and S1), our data indicate a general homogenous motion of Calabria toward the NNE at a rate of ~5 mm/yr (in a Eurasia-fixed reference frame), with the exception of the Crotone station (KROT), which moves at a velocity of 8.08 mm/yr toward the NE (Figure 1a). To test the hypothesis that this station was influenced by a local cause, we computed the mean regional velocity for the other seven GPS stations (4.9 mm/yr) and then calculated the residual local velocity of each of the eight stations by subtracting the mean regional velocity from the measured ones. Residual velocities are nearly null (≤1 mm/yr) at all stations, except KROT, which has a residual velocity of 4.84 mm/yr toward the east (Figure 1b). To understand the cause of the anomalous KROT velocity, we examined the onshore geology of the Crotone basin and integrated it with our interpretation of offshore seismic reflection profiles and well logs (Figures 2, S2, and S3).

[5] The Crotone basin has developed since the Serravallian on top of the SE verging Calabrian accretionary prism, which grew along the Neogene subduction zone between the sinking Ionian lithosphere and the overriding European plate [*Minelli and Faccenna*, 2010]. Sedimentation in the Crotone basin started in the Serravallian with predominantly continental deposition and evolved during the Neogene to Quaternary into shallow marine deposition with interbedded continental sediments. The Messinian salinity crisis caused the deposition of a thick evaporite-dominated formation. The base of this formation in the middle of the basin lies at a maximum depth of ~2000 m below sea level (bsl), whereas the formation reaches a maximum thickness of ~1300 m (Figures 2b and S3) and thins both landward and seaward. Salt structures as large-scale

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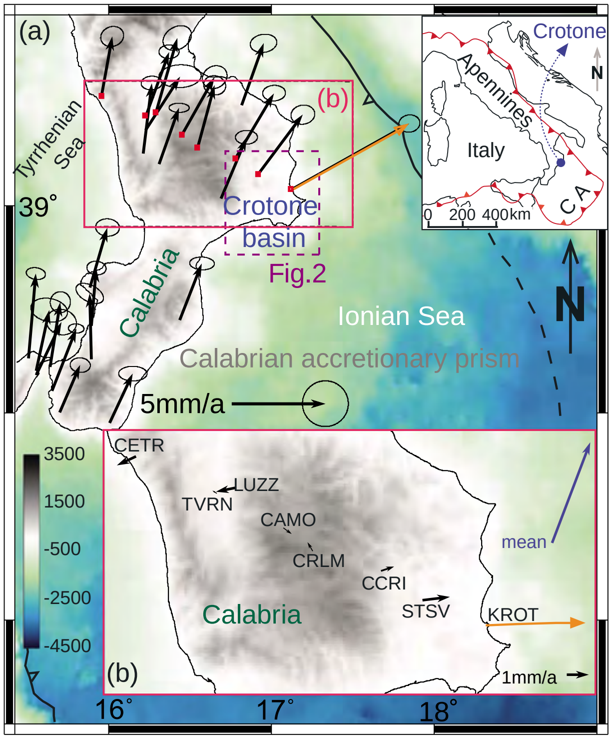

**Figure 1.** (a) GPS velocities (error ellipse 95%) for Calabria (see also Figure S1) in a Eurasia-fixed reference frame [*D'Agostino et al.*, 2011]. Inset shows a schematic map of the Apennines-Ionian-Maghrebides subduction system. CA = Calabrian Arc. (b) Residual (local) GPS velocities (Table S1) obtained by subtracting the mean regional velocity (blue arrow, calculated excluding the KROT station) from the total velocities measured at the stations. The eight GPS stations shown by red dots were installed for the Calabrian Arc Project.

gravitational structures have been documented over the onshore portion of the basin, where also ascending diapirs are exposed and mined [*Zecchin et al.*, 2003]. NE striking normal faults, which become younger seaward, form an upslope extensional domain in the northwestern sector of the Crotone basin (Figure 2). These faults have controlled the basin subsidence and evolution, particularly during post-Messinian time [*Zecchin et al.*, 2012]. Some of these faults reactivated previous thrust ramps formed during a north and NW verging thrusting phase [*Reitz and Seeber*, 2012]. The basin is bounded to the northeast and southwest by NW trending diffuse zones of strike-slip deformation [*Van Dijk et al.*, 2000; *Speranza et al.*, 2011]. Coupling field data with available onshore seismic reflection profiles and well logs, we constructed a NW-SE geological cross section showing the Crotone basin setting (Figures 2a and 2b).

[6] The Crotone basin and its offshore expansion have been extensively investigated for oil exploration, and most well logs and seismic reflection profiles are publicly available (http://unmig.sviluppoeconomico.gov.it/videpi/). We calibrated the seismic stratigraphy of the offshore portion of the Crotone basin using the Leda and Lulù wells (Figures 2, S2, and S3). Leda well penetrated a Pliocene-Quaternary unit (claystone and sandstone) and underlying thicker-than-normal (thickness exceeds 1300 m) Messinian succession (clay with evaporite and salt layers) before reaching the pre-Messinian basement. Projecting the time-calibrated Leda well onto the F75-66 profile, N-S oriented (well-to-profile distance = 500 m; Figure 2c), the peculiar thickness of the Messinian deposit can be explained as a result of a series of landward dipping thrusts, which result in doubling the thickness of the Messinian unit above a main basal décollement localized along an infra-Messinian evaporite layer at a depth of about 1650 m bsl. In particular, projecting the Lulù well onto the east striking F75-113 profile (Figure 2d), it arises that a sheet of mobilized Messinian and Pliocene-Quaternary deposits has been seaward thrusted over the pre-Messinian and Plio-Pleistocene stable units. Seaward thrusting, which involves the Messinian evaporite and its sedimentary cover (Pliocene-Quaternary), is visible on all offshore seismic profiles (Figures 2 and S2).

## 3. Discussion and Conclusions

[7] We interpret the presented data (Figures 2 and S2) as a lobate megaslide (~1000 km$^2$) that is presently moving radially toward the Ionian Sea along an infra-Messinian evaporite layer (Figure 3). The megaslide includes a downdip toe-thrust domain along its offshore margin and an updip extensional domain (Figures 2 and 3) [e.g., *Brun and Fort*, 2004; *Vendeville*, 2005; *Cobbold et al.*, 2010]. The megaslide rests on the pre-Messinian Calabrian accretionary wedge [*Minelli and Faccenna*, 2010]. The geometry of the basal salt décollement, as shown by well log data, is concave upward, dipping seaward in the extensional domain (onshore portion) (Figures 2b and S2) with a gentle southeastward slope of ~2.5°. It becomes flat to gently landward dipping in the compressional domain, where the décollement depth, obtained by the well logs, ranges between a maximum of ~1750 m bsl, close to the coast, and a minimum of ~1300 m bsl, along the frontal thrust emergence (Figures 2a and S2).

[8] The megaslide or part of it has probably been active since early Pliocene time, as shown by activation and growth of onshore normal faults during the Pliocene [*Zecchin et al.*, 2012]. Several lines of evidence indicate that the megaslide is still actively gliding: (1) the steep bathymetry off Crotone without marked submarine canyons [*Morelli et al.*, 2011], (2) the seaward tilting of Pleistocene marine terraces in the Crotone basin [*Zecchin et al.*, 2012], (3) the late Holocene subsidence of the Crotone coastal area (4 mm/yr) [*Stanley and Bernasconi*, 2012] in contrast to contemporary uplift of Calabria [*Ferranti et al.*, 2006], and (4) the emergence of the toe thrusts on the seafloor (Figures 2 and S2).

[9] We explain the GPS residual velocity at the KROT station (4.84 mm/yr toward the east; Figure 1b) as a result of the present seaward gliding of the megaslide over the Messinian evaporite layer (Figure 3). Moreover, the residual velocity measured at KROT (~5 mm/yr) is in good agreement with salt-related gliding deformation rates previously estimated with interferometric synthetic aperture radar methods or deduced from cross-sectional balancing and numerical modeling (i.e., between about 0.1 and 10 mm/yr) [e.g., *Rowan et al.*, 2004; *Furuya et al.*, 2007; *Albertz et al.*, 2010]. Both the onshore geology and the offshore reflection seismic profiles (Figure 2) show that the Crotone megaslide is a complex structure characterized by different thrust sheets. The KROT GPS local velocity may therefore reflect the movement of only a portion of the megaslide.

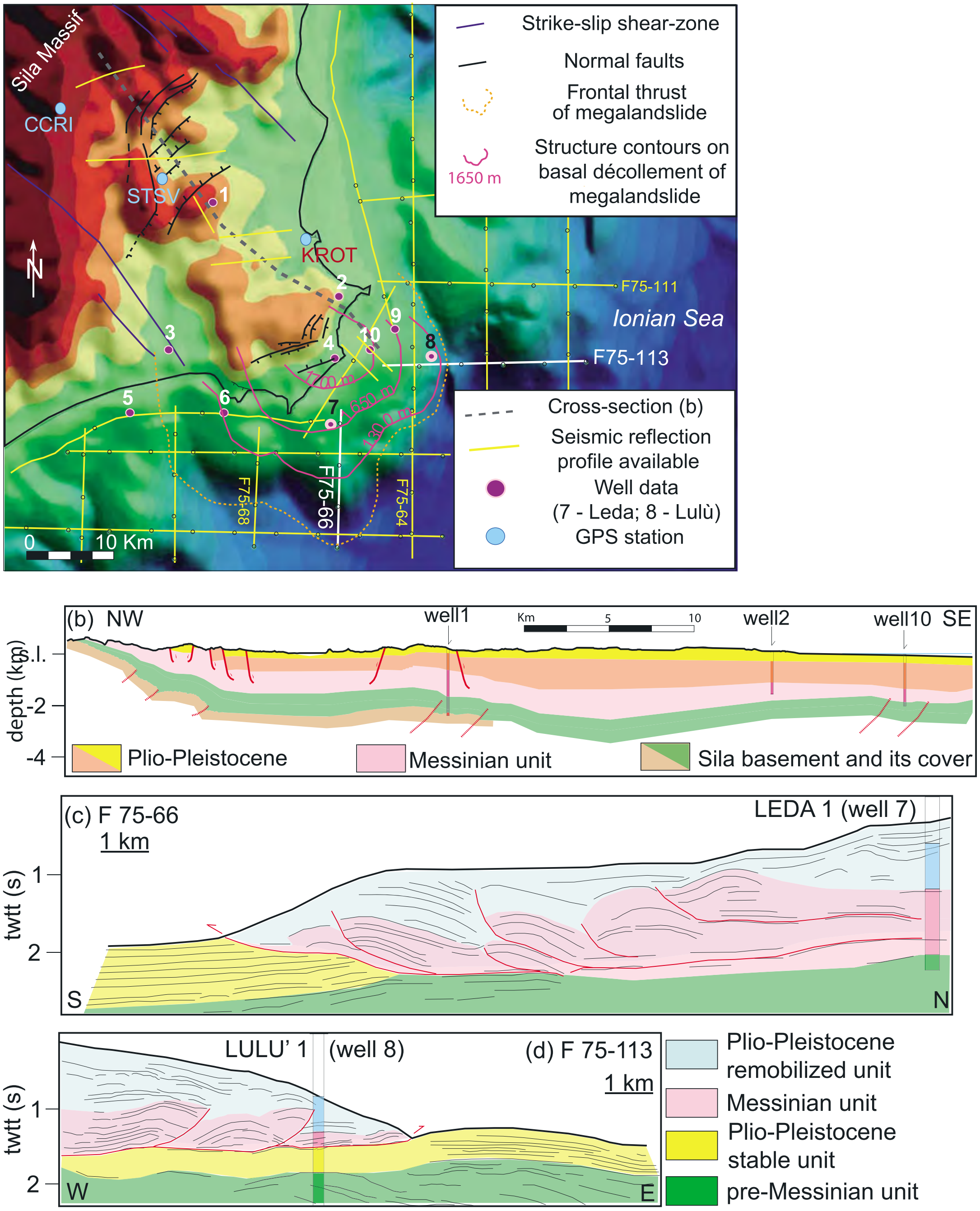

**Figure 2.** (a) Location map of the publicly wells and seismic reflection profiles analyzed in the Crotone basin (in white profiles F75-66 and F75-113 shown in Figures 2c and 2d) and three of the eight GPS stations (KROT, STSV, and CCRI). All the seismic reflection profiles shown in the position map are available at http://unmig.sviluppoeconomico.gov.it/videpi/. Simplified tectonic setting modified from *Zecchin et al.* [2012, and references therein]. The orange dotted curve is the frontal toe thrust of the salt-detached megaslide identified in the seismic profiles and well logs (Figures S2 and S3). Violet lines are structure contours of the basal salt décollement (depths interpolated from well logs). Well names: 1 = Crotone, 2 = Perrotta, 3 = Botricello, 4 = Torre Cannone, 5 = Lola, 6 = Liliana, 7 = Leda, 8 = Lulù, 9 = Lucilla, 10 = Liana. (b) NW-SE geological cross section through the Crotone basin, constructed using onshore seismic reflection profiles and well log data. See Figure 2a for the cross-sectional track. Note that this cross section does not include, toward the southeast, the offshore toe-thrust domain of the salt-detached megaslide. (c) Line drawing of a N-S seismic reflection profile F75-66 (see location in Figure 2a and original seismic data in Figure S2) calibrated with the Leda well. (d) Line drawing of an E-W seismic reflection profile F75-113 (see location in Figure 2a and original seismic data in Figure S2) calibrated with the Lulù well.

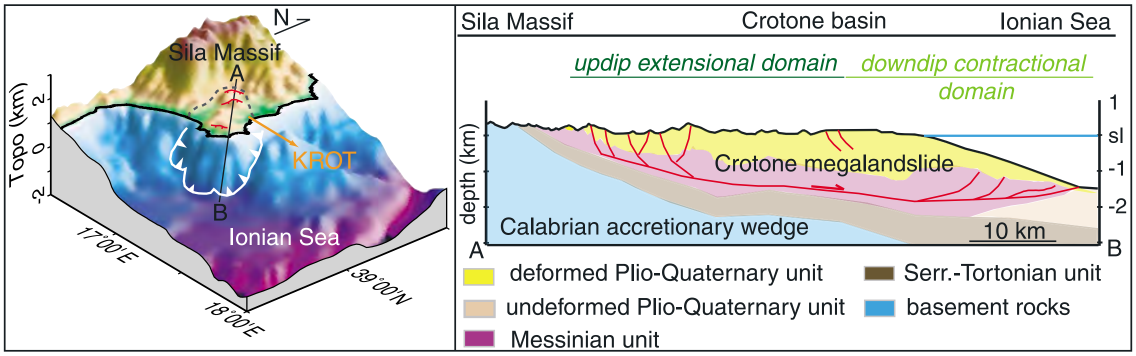

**Figure 3.** Three-dimensional model and conceptual cross section showing the Crotone salt-detached megaslide. An eastward velocity of 4.84 mm/yr locally recorded by the GPS KROT station is interpreted as due, at least in part, to the ongoing seaward movement of this megaslide (or part of it).

Moreover, it is not clear whether the megaslide motion has been continuous or has occurred through pulses.

[10] Concerning the possible trigger of the Crotone megaslide, we believe that one important factor has been and still is the gravity instability [e.g., *Mauduit et al.*, 1997; *Brun and Fort*, 2004] progressively generated by the uplift of Calabria during orogenic convergence and related crustal-scale shortening [*Minelli and Faccenna*, 2010]. The base of the Messinian formation, which is inclined by about 2.5° (Figure 2b) in the onshore portion of the basin, and the progressive seaward shift of the basin depocenter over time [*Zecchin et al.*, 2012] both testify to the significant uplift that has occurred in this region during Pliocene and Quaternary times [*Ferranti et al.*, 2006]. Our data (i.e., the slide downslope expansion), however, suggest that the megaslide is not simply gliding downslope; rather, it is radially spreading over the Messinian evaporite layer as is typical of salt tectonics [*Gaullier and Vendeville*, 2005].

[11] Our results provide direct constraints on the mechanical properties of the salt décollement. As a rheological test of our arguments, we estimate the viscosity of the Messinian evaporite using the equation for the viscous behavior of rock salt $\eta_{salt} = \tau/\varepsilon$, where $\tau$ is the shear stress on the salt décollement, and $\varepsilon$ is the strain rate [*Turcotte and Schubert*, 2002]. In the case of the Crotone basin, the overburden density and thickness are 2500 kg/m$^3$ and 1000 m, respectively, and the basal décollement slope angle is 2.5°. The GPS-measured velocity is ~5 mm/yr, and the viscous salt layer thickness is at least 500 m. Using these data to calculate $\varepsilon$ over the décollement, we obtain that $\eta_{salt}$ is ~$10^{18}$ Pa s, which is within the known range of $\eta_{salt}$ in nature ($10^{16}$–$10^{20}$ Pa s) [e.g., *Chemia et al.*, 2009; *Mukherjee et al.*, 2010].

[12] In conclusion, (1) an unknown actively gliding salt-detached megaslide is discovered in Calabria and Ionian Sea, Italy; (2) for the first time ever, the gliding velocity of a salt-detached large-scale structure (or a portion of it) is measured using GPS; and (3) for the first time ever, the viscosity of a large-scale salt décollement layer is derived from GPS-measured velocities and well matches the known range of salt viscosity in nature.

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