El Forn Landslide-Andorra

El Forn giant landslide, a DSGSD in Andorra. A review.

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Abstract

The document provides a detailed chronology of studies and findings regarding the El Forn and Encampadana landslides.

1. **Initial Studies (1984-1990):**
   - Corominas and Alonso (1984) first identified the landslide's large-scale features, though initially misinterpreted its origins (e.g., as a glacial feature).
   - Slope gliding was recognized earlier with signs such as historical edifications (Sant Miquel romanesque church, haystack), roads, hydroelectric pipeline-tunnel deformation at slow displacement rates (up to 5 mm/year).
2. **Comprehensive Research:**
   - Corominas (1990) expanded the study to include the Encampadana massif, revealing varying reactions of weaker (Silurian black silts) and harder (Devonian calcshists) massifs to paraglacial induced stress during successive deglaciation phases.
3. **Geomorphological Mapping (1994-2005):**
   - Santacana (1994) identified three main phases of slope instability, with Clariana et al. (2004) refining maps and linking the glided platforms to broader geological structures.
   - Turu & Planas (2005) used geophysical methods to profile the landslide, determining deposit thickness and establishing a chronology of past landslides dating back at least 13,319 years ago, however unstability is related to the final glacier recession several millennia before. A latter unstability (Riba Grossa) could be dated by the authors according to 9,550 yrs ago.
4. **Landslide Evolution (2011-2016):**
   - New datations form Planas et al. (2011) suggested a glacial origin for some morphological features from its foothill. The oldest glacial phases are according to the Late Glacial Maximum and Termination I periods.
   - Instrumental monitoring revealed an active displacements of 2–3 cm/month during heavy rainfall at Cal Borronet.
5. **Modern Investigations (2006-2021):**
   - Advanced models by Hürlimann et al. (2006) and McCalpin & Corominas (2019) explained deformation via deep-seated gravitational processes since the last deglaciation form at least 15,000 yrs ago.
   - Cal Borronet boreholes and measuring devices installation (2005–2008) encountered several issues. However, subsequent campaigns (Seguí et al., 2021) identified a sliding surface and determine its characteristics. The high velocity of the Cal Borronet landslide (24 cm/yr) is associated to groundwater pressure effects.

6. **Remote Sensing Advances:**
    - Ground-Based SAR (GBSAR) and satellite techniques (DInSAR, TerraSAR-X, Sentinel-1) monitored the general motion over the area, confirming displacements on El Forn's mid- and upper slopes.
    - Campaigns revealed instability affecting ski resort infrastructure and significant rock masses unnoticed earlier.
7. **Challenges with Measurements:**
    - Remote sensing and GPS data provided insights but faced limitations due to orientation and environmental factors. Uncertainty remains about long-term displacement rates and their damaging implications for infrastructure.

Key words: Monitoring, deep-seated gravitational slope deformation, remote sensing, paraglacial, active landslide

The chronology of the knowledge

Unravelled by Corominas and Alonso (1984), the landslide was discouraged by local geomorphologists because of its large size. Its head scarp was misattributed to a glacial cirque, and its lobulate tongue was interpreted by pioneering authors as a giant solifluction landform. Moreover, an existing church from the 12th century and prehistoric sites from the Bronze Age at the main village (Prats, 1572 m asl) are unaware of significant slope instabilities (Yañez et al., 2002); **Figure 1**.

However, slope gliding was known earlier. By the end of the second half of the last century, a handmade pipeline crossover from north to south of the El Forn de Canillo giant landslide (2700 km²) testified to the advancement of its toe. It was repaired several times, and the overall effects of the deformation on the pipeline included a reduction of the working section at the northern border and a displacement rate of 0.25 to 0.53 cm/year on the southern boundary (**Figure 1**). However, such data remained unpublished for 64 years and was used only by the owner, a private power plant (FHASA), until its nationalisation in the 1990s (FEDA).

Expanding the study area to the Encampadana calcareous schist massif, Corominas (1990) presents a comprehensive study. He advises on the synthetic and antithetic faulting affecting this massif, which produces sakung and antiscarps. For Jordi Corominas, both massifs reacted accordingly to their mass strength through lateral expansion during deglaciation. The weaker massif experienced a landslide, while the stronger massif expanded laterally but remained cohesive. Despite this, during the 1990s, the local authority enlarged the road built ten years earlier to 1600 m asl, reaching 1900 m asl, creating recurring breaking points at Cal Ponet (1690 m asl) and Cal Borronet (1850 m asl).

Addressed by Jordi Corominas, the first geomorphological mapping of El Forn was by Nuria Santacana (1994), a significant contribution that sheds light on the complex landform involving 340 × 10^6 m³. Santacana's work revealed a landform produced by at least three phases of slope instabilities: two affecting the upper part of the mega-landslide (≈ 2300 m asl) running down to the valley floor (≈ 1500 m), the first involving friable black slates (Silurian), and the second affecting both calc shales (Devonian) and black slates. A third instability overlapped the second landslide by a sizeable rotational platform on top (2000-2300 m asl). However, ten years later, Clariana (2004) mapped the Encampadana massif and the El Forn landslide, including them in the eastern termination of the Tor-Cassamanya syncline, while renaming Santacana's cartography.

Based on geophysical data, Turu & Planas (2005) produced the first comprehensive profile following Santacana's mapping. The electrical resistivity of the down-glided materials allowed Turu & Planas (2005) to determine a thickness of at least 175 m of landslide deposits. The authors also provided the first chronology, which includes numerical dates. The two early landslides were older than 12968 - 13319 years (cal BP), and a fourth landslide dated between 9550 and 9959 years (cal BP) was identified by these authors at Riba Grossa (1700 m asl), affecting the mega-landslide's mid-tongue.

Corominas & Planas (2011) and Corominas et al. (2013) report the results of the first soundings, inclinometer monitoring (**Figure 2**), and new AMS data. The well-known active area on the northern side at mid-slope (Cal Ponet – Cal Borronet) slides intermittently 2-3 cm/month during heavy rainfall. However, the authors also provided a new interpretation of the mega-landslide's lobulated tongue, indicating it is of glacial origin (**Figure 3**). Corominas & Planas (2011) observed erratics spreading below 1630 m asl with allochthonous lithologies (granite), suggesting a glacial modification of the tongue of the second landslide (erratics, **Figure 3**). According to these authors, the valley glacier receded and advanced over the glided sediments and, at its last advance, built an end-moraine at La Sella (1530 m asl). By using the data from Planas et al. (2011), Turu et al. (2016) dated the landslide affecting the black slates to the MIS 3 end (34.26 – 39.66 ka cal BP), while the second landslide is dated to an early LGM age (25.94 – 25.40 ka cal BP). For these authors, the final valley glacier retreat promoted the ponding of a lake during the Alleröd (12968 – 13319 yrs cal BP), which was dammed by the La Sella end-moraine (at the end of the lowest-most glacial ridge, **Figure 3**). The La Sella end-moraine was partially eroded before 5.7 ka from cosmogenic ^{36}Cl data.

The modelling and instrumental experiences from Encampadana

The first deformative model representation for Encampadana is from Hürlimann et al. (2006), interpreting it as a deep-seated gravitational slope deformation (DSGSD) with a ductile core (black slates), which facilitates the grabben-like structure at the top of the slope and many large counterscarp that can be seen from the opposite slope. The deformation structures were dated by McCalping & Corominas (2019), and three trenches were excavated across antislope scarps and adjacent troughs. Both studies (Hürlimann et al., 2006 and McCalping & Corominas, 2019) advocate slope toppling of tilted domino blocks to explain the observed scarps and troughs. Fine-grained upward sequences of strata were the common infill of these troughs (McCalping & Corominas, 2019). Following these authors, it seems that deformation affected the lower part of the Encampadana massif first (1935 m asl) just at the end of the HS1 (or Oldest Dryas), at 15.3 ka cal BP, and spread until its summit (2320 m asl) by 11.6 ka (the Younger Dryas end). The last observation, the upward trend of fracturing, aligns with other DSGSD kinematics (McCalping & Corominas, 2019). For Encampadana, this occurs because the downhill end of the slope is most oversteepened due to glacial erosion.

The modeling and instrumental experiences from El Forn, promoted by the Andorra government between 2005 and 2008, included drilling ten boreholes (264,940.36 €) to depths of 40 to 60 m. These boreholes were equipped with inclinometers, rod extensometers, and piezometers to locate the sliding surface and characterize the glided materials, as engineered by a private consultant (107,688.69 €; 2002-2013). One borehole (S2) extends investigations to 200 m in depth (**Figure 1**), where the basement is at 150 m, while a second borehole (S8) is at 175 m, reaching the basement at a depth of 115 m (Torrebadella et al., 2009). However, some equipment did not function correctly; during the onset of the subprime crisis in 2008, the local owner of the public tender failed to fully pay the foreign drilling company (Geotech-262). The monitoring network was deemed insufficient due to equipment malfunctions leading to unreliable measurements. However, the most active lobe (Cal Ponet – Cal Borronet) has a functioning extensometer (S10) showing significant deformations. Further research was conducted by Seguí et al. (2021) on this gliding lobe, using new sounding data from FEDA that allowed the identification of the "décollement" boundary at a depth of 30-27 m. The recovered phyllosilicates were studied petrologically, revealing that the sliding surface consists of two bands with behavior similar to those produced in shear zones related to folds (Seguí et al., 2021). The borehole from the first campaign (S10) at (-50 m) was fully equipped, including an extensometer (-40 m), a thermometer (-30 m), and a piezometer sensor (-35 m) that measured water pressure (**Figure 2**). The results indicate that displacement (Δd= 3 mm) and temperature (ΔT = 0.04ºC) vary proportionally over time (60 days), in parallel with water pressure below the sliding surface (Δpw = 10 m of water column). These researchers predicted a minimum sliding thickness of 16 cm under current conditions and confining strata below; however, a thicker sliding surface indicated by sounding data may suggest an unknown triggering overload (earthquake) or an increase in groundwater pressure.

The El Forn remote sensing data

The unique working extensometer (S10) signalled a slip velocity of 2 cm/month (May – June 2009) following sudden snow melting and intense rainfall events (**Figure 2**). Due to the lack of comparison from a non-functioning monitoring network, the best option in 2009 was to increase data point densities using SAR sensors. One of the first available deformation monitoring datasets from Ground-Based Synthetic Aperture Radar (GBSAR) comes from the El Forn mega-landslide foothill (Crosetto et al., 2014). The radar was installed on the opposite side of the valley (at 1560 m asl), on a stable slope, processing sets of radar images acquired during intermittent campaigns that visited the site periodically (on the 29th of September, the 21st of October, and the 25th of November 2009). However, discontinuous GBSAR requires the support of artificial corner reflectors. In contrast, D-BSAR avoids the effects of severe atmospheric fluctuations in long-term GBSAR datasets, which need correcting the resulting phase differences when retrieving interferometric information and applying differential-SAR-interferometry (DInSAR). Many DInSAR methods are also known as Persistent Scatterers Interferometry (PSI), such as the work by Iglesias et al. (2012, 2014), who installed a radar atop the opposite valley cliff (1910 m asl) and recorded data between 2007 and 2011. Both methods (D-GBSAR and DInSAR) highlight the rapid movement of the Cal Ponet - Cal Borronet, but DInSAR also documented an unexpected movement atop the El Forn mid-slope. Moreover, to validate the DInSAR data, the authors compared it with data acquired by the TerraSAR-X sensor over a year (October 2010 – October 2011), highlighting extensive and unexpected displacements at the topmost area of El Forn, referred to as the third movement of Santacana (1994). Although the Andorra Government did not approve of any of the D-GBSAR and DInSAR campaigns, the official risk management quickly changed, abandoning borehole-based monitoring in favour of remote sensing (Corominas et al., 2013; Mallorquí et al., 2017). A two-year GPS field campaign between October 2014 and 2016 was extended to the crests above 2000 m asl, embracing an existing ski field resort (Clots Fondos, Maians, and Encampadana) to confirm the velocity displacements measured by the TerraSAR-X satellite (co-granted by the Andorra Government for 45,537.97 €) affecting an unstable surface of 400,000 m² containing millions of cubic meters of rock mass whose existence had remained unnoticed until then (Corominas et al., 2015; **Figure 3**).

Critical analysis of remote sensing data

A warning about the standard deviation of satellite measurements is necessary because it depends on the sliding movement direction (W-NW) and the polar orbital direction (azimuth). Measurements are sensitive only to the satellite-to-target displacement component (line of sight, LOS). Landslides oriented E-W are the most sensitive to polar orbital sensors, with a standard deviation of approximately 2 to 5 cm. If the direction is N-S, the standard deviation could be five times greater, which is unsuitable for measuring small deformations. This allows all measurements to reach the maximum scaled value, providing a general picture of monolithic movement (the scale maximum). When crossroad directions between the unstable slope and the satellite orbit occur, we only know that the hill's motion moves away from the orbital direction. Furthermore, if any activity on the mountain (such as solifluction, snow avalanches, or rockfall) has occurred, it will add uncertainty to the data measurements.

It is important to investigate whether the published maximum scaled deformation of 4 cm/year is reliable since the local authority built the ski resort in 1998. An expected 70 cm of displacement may affect the concrete buildings. In 2015, the author posed a series of straightforward questions to the director of the ski resort located on the hilltop of El Forn, such as concerns about the tilting of Winteregg's tower or cable-lift displacement. Is there any reported damage to the pipelines for artificial snowmaking? Are there any tension cracks on the slope or linear erosion affecting the steepest slope direction? Is the settlement affecting the buildings? The ski resort director answered all questions, affirming that several incidents could be compatible with slope motion, such as the frequent (once or twice a year) repairs to the snow-making pipeline. However, factors related to seasonal permafrost affecting the active layer or deficient construction could also impact the pipeline.

Results from GPS data align with information from TerraSAR-X and Sentinel-1 satellites (Zhao et al., 2019). However, the scattered GPS data makes it impossible to validate all satellite measurements on top of El Forn. Unfortunately, satellite and GPS data from Encampadana remain unpublished. Nevertheless, satellite data at El Forn is in the range of "stable" values (± 2 cm). According to Mr E. Barbier, the ski resort director's observations, the surrounding downhill ski slope reaches the highest values. Overall, the Cal Ponet – Cal Borronet area located at the foot of the hill showed noticeable displacement (Zhao et al., 2019), as identified by previous authors, moving downhill.

Discussion

The study of the Large-scale rock slope failures (RSFs) in the eastern Pyrenees (Jarman et al., 2014) identify a sparse but significant areas affected by RSF related to paraglacial and parafluvial contexts. Jarman et al. (2014) identify around 30 significant cases (>0.25 km²) and about 20 smaller or uncertain ones across the eastern Pyrenees. RSFs are absent from the range divide and main valleys, instead occurring in transitional zones like trough-head thresholds and pre-glacial summit surfaces; however, this is not the case for El Forn and Encampadana DSGSD, which provide insights of glacial and fluvial interactions into localized stress concentrations, as the Soldeu fault. Further south, Turu and Peña-Monné (2006) point out that the youthing of relief may related to neotectonic activity too, overprinted to the glacial and fluvial erosion.

Conclusions

Fourty years studing the El Forn highlights the evolution of techniques and challenges in understanding complex slope dynamics, emphasizing the role of multidisciplinary approaches (engineering, geology, geomorphology, geochronology, geoarchaeology). Interaction between glacial and fluvial processes shaping mountain landscapes may be the main trigger for DSGSD. However, a comprehensive evolution and reconstruction of the original slope is still pending, its exercice will shed light on to the origin of the tectonic motion of the area.

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Figure 1: Inventory of field data and monitoring on the El Forn giant landslide (in Catalan), in red piezometers, in yellow extensometers, in blue soundings and bedrock contact, some other data in red and yellow related to groudwater wells and hydroelectric pipeline, thanks to Xavier Planas i Batlle from the Andorra Government.

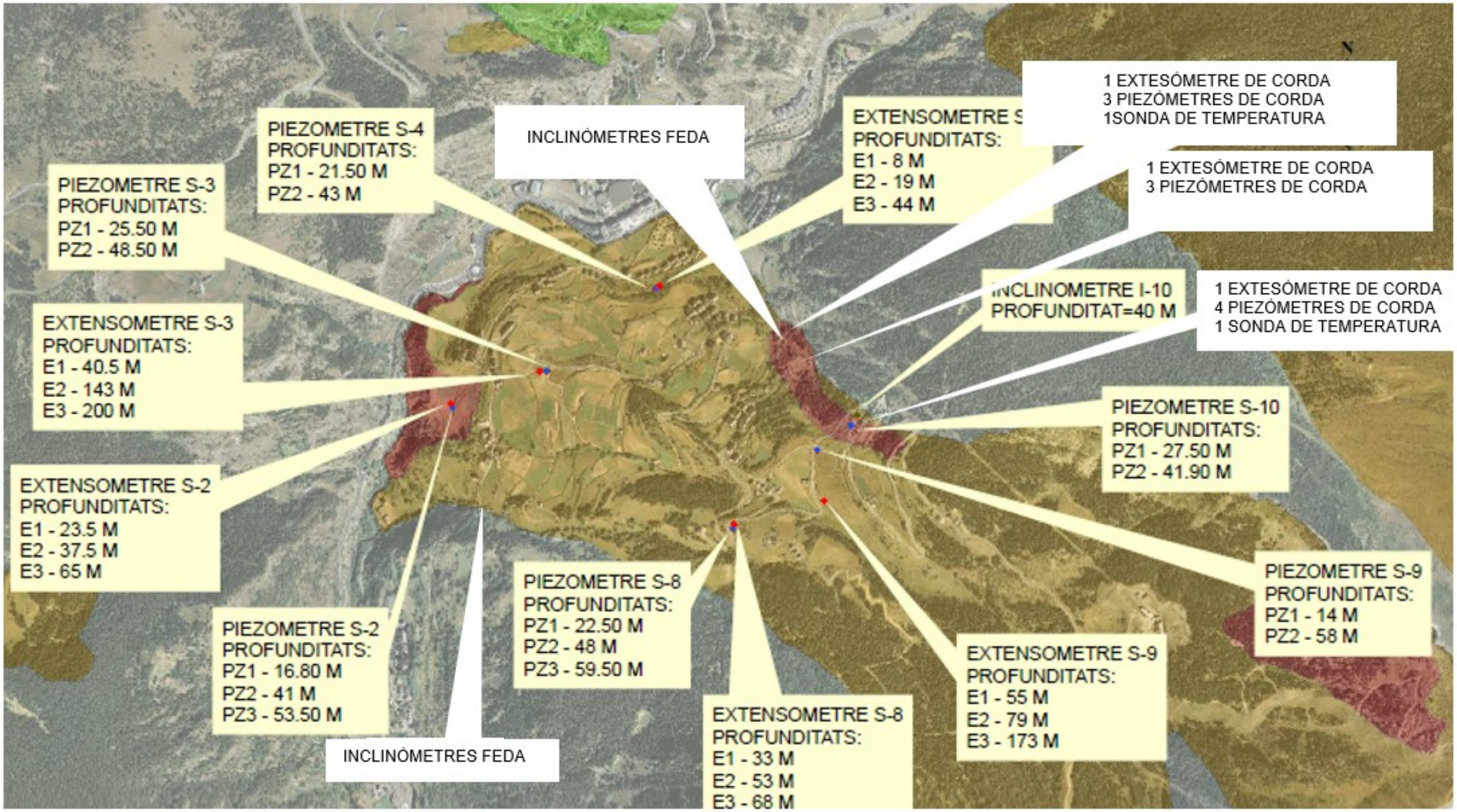

Figure 2: Detailed distribution of the monitoring network (in Catalan) and the most active areas from the El Forn landslide (in red), thanks to Xavier Planas i Batlle from the Andorra Government.

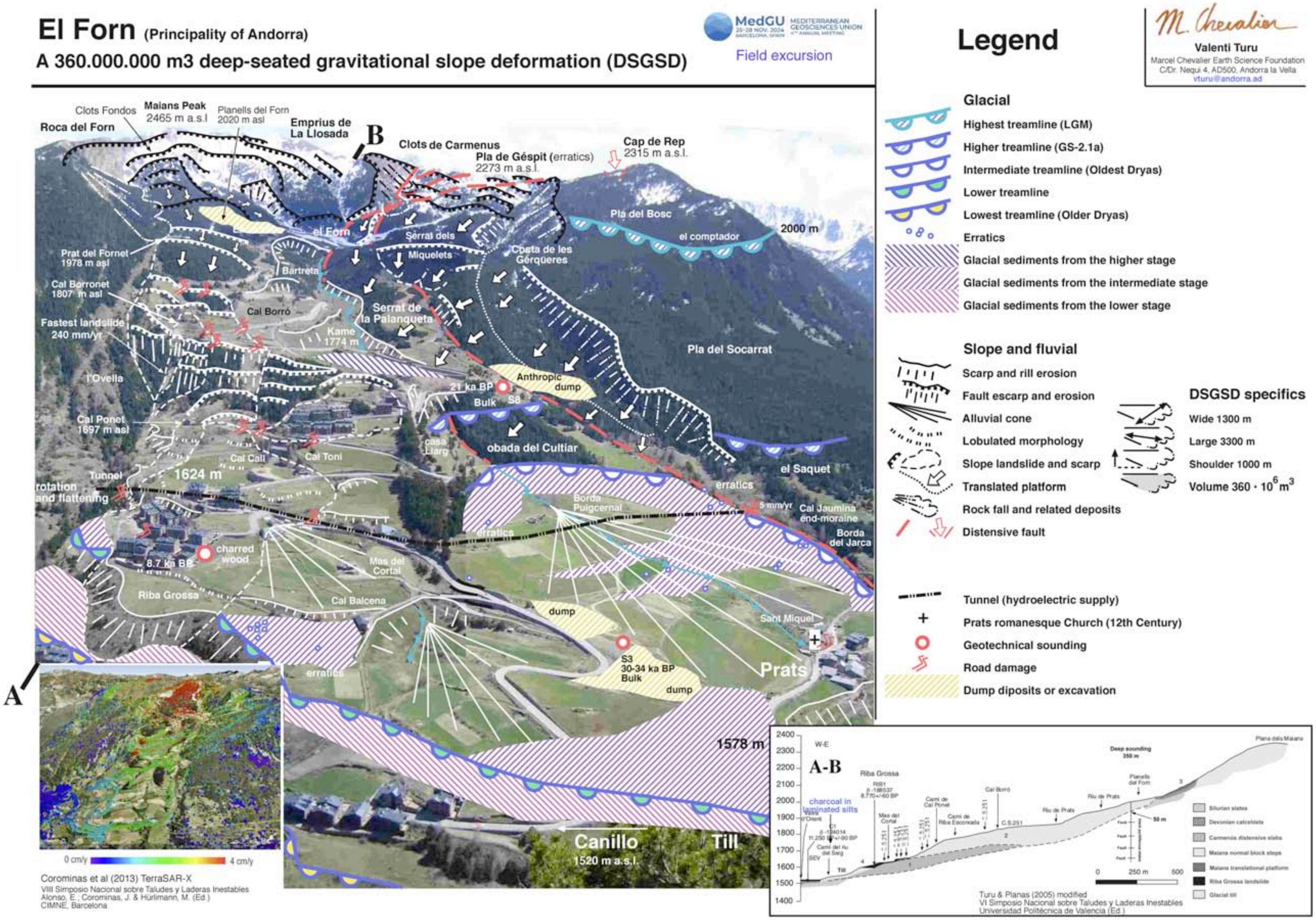

Figure 3: Geomorphologica interpretation of the el Forn giant landslide over a picture taken from the oposite slope of the valley.