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The Son Poc rockfall (Mallorca, Spain) on the 6th of March 2013: 3D simulation

Abstract The Son Poc rockfall took place on the 6th of March 2013 in the municipality of Bunyola, on the southern side of the Tramuntana Range (Mallorca) and after a rainy and cold period on the region. A volume of rock of 4.000m^3 was detached from the cliff crowning the peak falling down by toppling. The impact of the boulder caused its fragmentation, and numerous boulders bounced and rolled downslope with volumes from 1 to 35m^3, following two trajectories: southwest (SW) and southeast (SE). The SE trajectory, with a larger runout (376m), reached an urban area, where some of the boulders hit the roofs and walls of nearby houses, stopping others in their gardening areas. Fortunately, no fatalities occurred despite of the presence of some people at that moment, but the event caused great concern in a region which lives from and for tourism. The Son Poc rockfall has been simulated using RocPro3D software which uses GIS technology to produce 3D rockfall trajectories lines, estimated velocity and energy of falling blocks, as well as bounce heights, impacts, and stopping points. The results are in agreement with field observations and with a very good accuracy between real and modeled outcomes.

Keywords Rockfall · 3D simulation · Mallorca

Introduction

Rockfalls are geomorphological processes that represent a major hazard in mountain areas worldwide (Whalley 1984). Rockfalls range from small cobbles to large boulders hundreds of cubic meters in size and travel at speeds ranging from few to tens of meters per second (Guzzetti et al. 2002). Despite their often relatively small size, rockfalls are among the most destructive mass movements. In some countries of the Mediterranean region, such as Italy and Spain, rockfalls are the main cause of landslide fatalities (Guzzetti 2000a, b; Corominas 2000).

The island of Majorca is located in the Western Mediterranean and presents a variety of different geomorphological domains. The Tramuntana Range is located in the northwestern part of the island (Fig. 1) and presents a steep topography, which together with its geological complexity and Mediterranean climate favors intense slope dynamics (Mateos 2002). The main income of the island of Majorca comes from tourism as it welcomes 11.3 million visitors each year. The vast urban development that the Tramuntana region has undergone in the past 30 years has considerably increased the mass movement risk.

Rockfalls are the most frequent slope movement in the Tramuntana Range according to Mateos et al. (2012) due to the predominance of Jurassic rocky massifs made up of limestone and dolostone. Historically, there are records of numerous rockfalls on the range. That is the case of the huge rockfall on the Valldemossa area which took place on the 16th of March 1857. This rockfall razed and buried a large extension of cropland, leaving reports in the daily news. More recently, numerous rockfalls have made the news as well, such as the one in Cala de Banyalbufar in September 1993 (with a volume of 80 m^3), which affected several fishing huts and the rockfall in Son Matge (Valldemossa) in 2005, in which one of the most important archaeological sites from Majorca's prehistory was buried (Mateos et al. 2012). Between 2008 and 2010, the island of Majorca experienced the coldest and wettest winters of the last 40 years. Accumulated rainfall was twice the average, and values of intense rainfall up to 296 mm/24 h were recorded, very similar to those calculated for a return period of 100 years. Additionally, high precipitation coincided with anomalous, low temperatures, with abundant snowfall and freezing in the highest zones of the Tramuntana Range. As a result, 34 mass movements were recorded on the range, which seriously affected the road network as well as some dwellings (14 rockfalls, 1 rock avalanche, 15 landslides, and 4 karstic collapses were inventoried). The largest rockfall was at Son Cocó on the 19th of December 2008, which involved 300,000 m^3, and it was classified as a rock avalanche. It left a tongue of enormous blocks (some of them were >1,500 m^3) with a runout of almost 650 m, razing the surface of a pine wood measuring around 60,000 m^2 (Mateos et al. 2013b). These events reveal a greater exposure of vulnerable structures (dwellings, tourism resort, roads, etc.) on rockfall-prone areas on the Tramuntana Range, due to the important urban development occurred in the past decades (Mateos et al. 2013a).

This work describes the Son Poc rockfall which occurred on the 6th of March 2013 on the southern side of the Tramuntana Range (municipality of Bunyola). The rockfall initiated by toppling of a large boulder from a steep rocky escarpment. The impact of the boulder at the base of the escarpment produced its fragmentation, and numerous boulders bounced and rolled downslope stopping at the foot of the slope and hitting several dwellings. Fortunately, there were no deaths, despite of some people were inside the houses at that moment.

In order to simulate the dynamics of the Son Poc rockfall, a three-dimensional physically based model was implemented using RocPro3D software. As a result, the three-dimensional trajectories and the derived analysis maps (energy, velocity, impacts, stopping points, etc.) were computed for every cell of the study area (Cottaz et al. 2010). These results have been validated with field observations getting a proper accuracy.

Geographical and geological setting

The Tramuntana Range is the main mountainous alignment of the island of Mallorca (Fig. 1) with a maximum length of 90 km and an average width of 15 km (1.100 km^2). The geological structure of this Alpine chain leads to a gentler southern slope than the coastal one, which is much more rugged and abrupt, with a prevalence of very high cliffs overlooking the sea. The peak line is over 600 m above sea level (a.s.l.), and the central sector is the highest (Puig Major peak, 1,445 m a.s.l.). The Tramuntana region encompasses 16

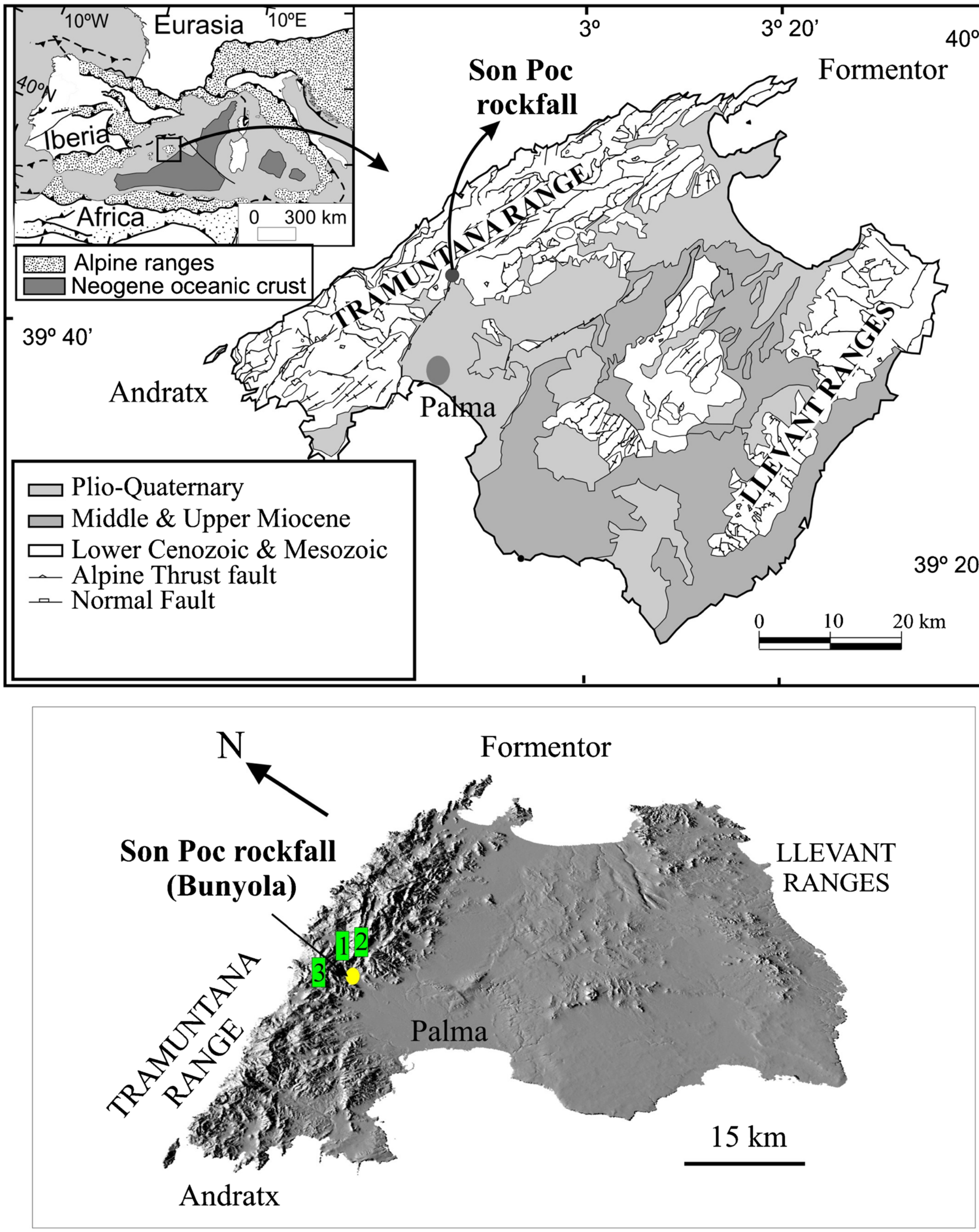
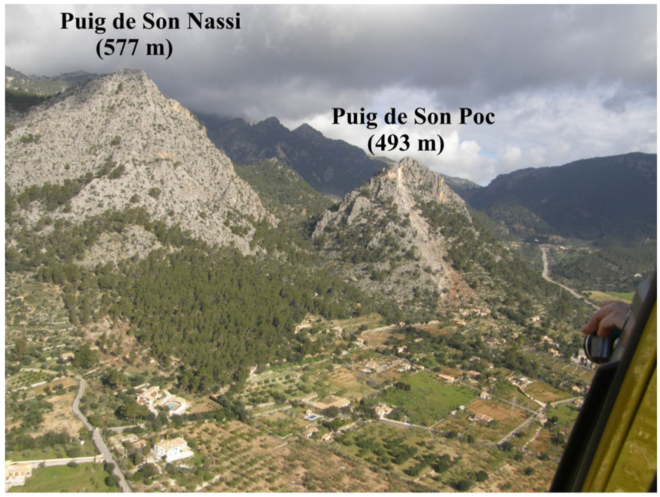


Fig. 1 Geographical and geological context of the Tramuntana Range in the island of Mallorca. Location of the Son Poc rockfall on the southern side of the range as well as the weather stations used for the present work: *1* Biniforani Nou (B249), *2* Bunyola-Raixa (B260), *3* Palma-Universidad (B236C)

municipalities with a total population of 115,000 inhabitants, being the northern face much more heavily populated and urbanized. The economy of the Tramuntana region targets primarily tourism, which accounts for 95 % of its income (Mateos et al. 2013a).

The Tramuntana Range corresponds to the reliefs caused by the Miocenic structuring linked to the Alpine fold, formed by a series of NW-overlapping thrusts (Sàbat et al. 2011). The stratigraphy of the Tramuntana Range begins with the deposits of siliceous sandstone from the Buntsandstein (Lower Triassic) until the more recent colluvium sediments from the Quaternary. Carbonated lithologies clearly predominate, especially Jurassic limestone and dolostone, which constitute the framework of the mountains. The NE-southwest (SW) mountain alignments correspond to the overlapping system (Fig. 1), and the regional detachment level are the later Triassic (Keuper) sediments, clay, and gypsum with volcanic rock.

The Son Poc rockfall took place on the southern side of the Tramuntana Range, in the municipality of Bunyola (Figs. 1 and 2). Son Poc is the name of a peak "Puig de Son Poc" with a height of 493 m a.s.l. The peak crown is formed by the Jurassic rocks from Lias formed by karstified dolostones with vertical bedding that



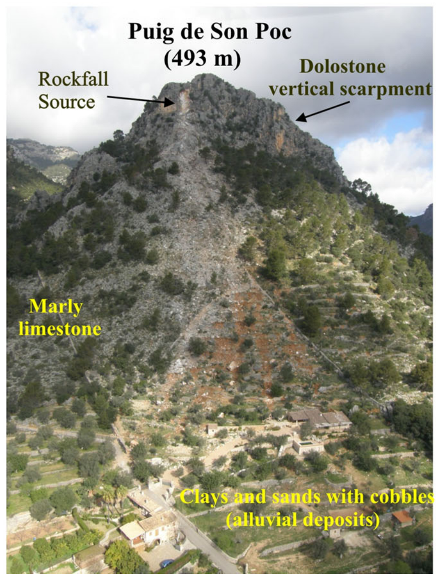


Fig. 2 The Son Poc rockfall which took place on the 6th of March 2013. A volume of rock of 4.000 m^3 was detached from the cliff crowning the "Puig de Son Poc" affecting an urban area located at the base of the slope. A geological description of the slope is shown in the *lower photograph*

determines a very steep cliff (50 m high). At the base of this cliff, softer marly limestone from the Raethiense outcrop is characterized by a gentler slope with a length of 350 m. At the base of this slope, several houses are located in a plain area where alluvial and Quaternary deposits (clays and sands with cobbles) cover the area (Figs. 2 and 5b).

The rock massif constituted by the Liassic dolostone is affected by vertical stratification (N 130° E, 83° SW), and it is parallel to the slope face. At the top of the hill, this thin-bedded stratification is more persistent, and it is delimitated at the base by a fault N 85° E which dips 20° N (Fig. 3a). As a result, a toppling failure may result which involves rotation of vertical strata about the fixed base constituted by the fault. At the base of the hill, the rock splits are massive, and the rocky massif is karstified with the typical karren features.

Description of Son Poc rockfall event

The Son Poc rockfall took place on the 6th of March 2013 at 11:05 a.m. A volume of rock of 4.000 m^3 was detached from the cliff crowning the peak. A dolostone vertical strata, delimitated at the base by a fault (Fig. 3a), fell down by toppling. The impact of the boulder caused its fragmentation, and numerous boulders bounced and rolled downslope, following two trajectories (Fig. 3b): southeast along 376 m maximum and southwest up to 150 m long. The maximum topographical gradient is 225 m. The impact caused debris falls and boulder falls according to Rapp (1960), Gardner (1980), and Whalley (1984), as the block sizes varied from 1 to 100 m^3.

According to the boulder inventory (>5 m^3), most of them were concentrated in the lowest part of the slope (Fig. 4). Since the lowest part of the slope is terraced in the whole southern face, most of the boulders stopped on the terraces (Fig. 3d). These impacts caused 1-m-deep depressions in the land as well as drag marks (Fig. 3c and d). However, some of the boulders hit the roofs and walls of nearby houses (Fig. 3f), stopping others in their gardening areas (Fig. 3e). Fortunately, no fatalities occurred despite of the presence of some people in the area.

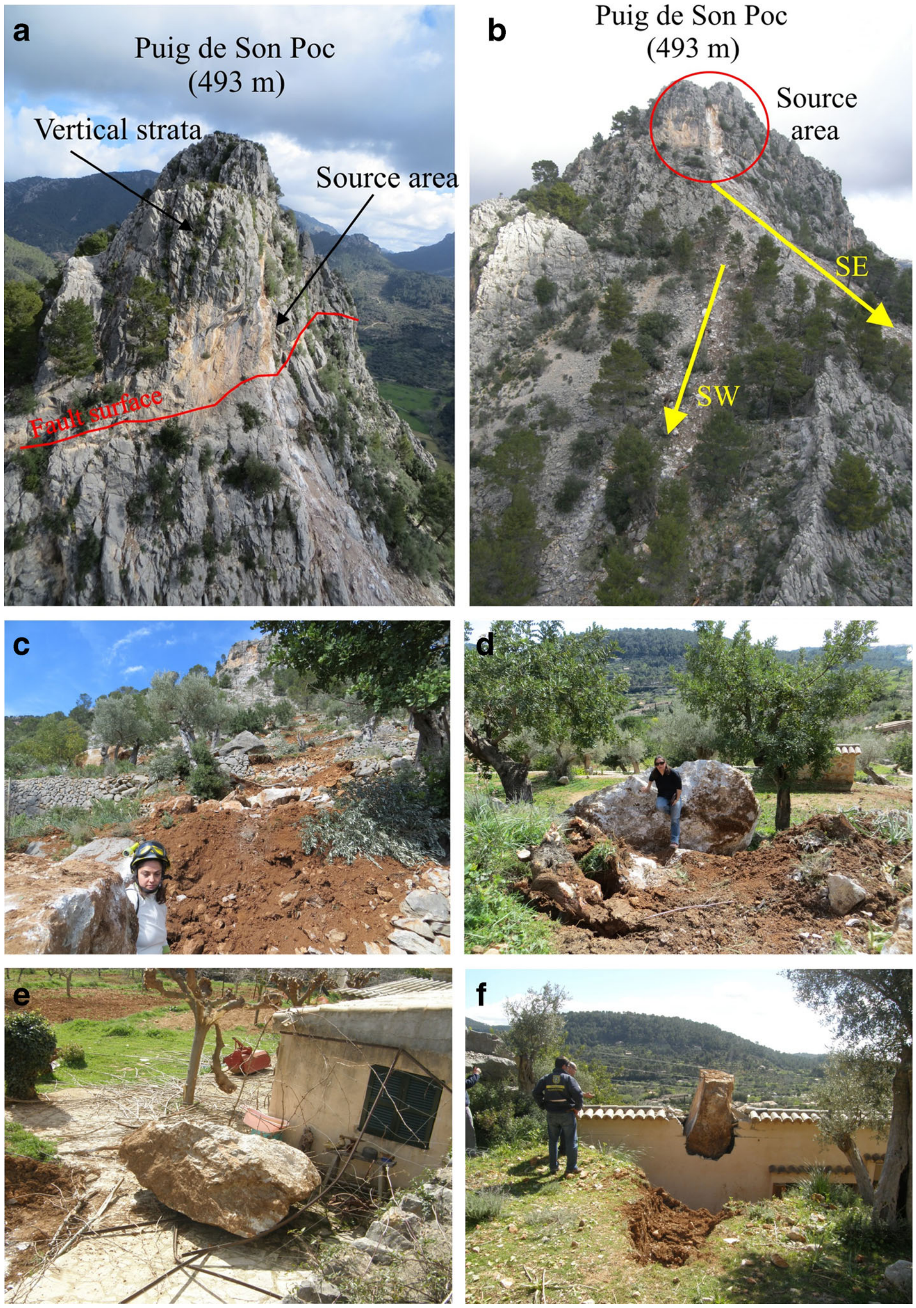


Fig. 3 **a** Dolostone vertical strata crowning the Puig of Son Poc, delimitated at the base by a fault. **b** Two rockfall trajectories. **c** Effect on the terraces by the bouncing and rolling of the blocks. **d** Impact on the ground causing a depression as well as drag marks. **e** One of the boulders in a gardening area. **f** A block of 8 m^3 crashed into the roof and the wall of a house located in the lower part of the slope

Exploratory field work revealed that rockfalls are recurrent in Son Poc. Numerous scarps can be observed at the cliff as well as scree deposits in the southwestern face of the slope (Fig. 3b). Old boulders have been also identified in the urban area located at the foot of the slope.

Taking into account that the main source of income in Majorca is tourism (83 % GDP), as it welcomes over 11.5 million visitors each year, the Son Poc rockfall caused great concern, with wide press coverage, contributing to a greater awareness of the risk that these processes involve, in an area where the safety of the island's population and its visitors must be the priority of all concerned.

Triggering conditions

Most of the rockfalls that commonly occur in the Tramuntana Range are triggered by the following: (a) rainfall intensity greater than 90 mm per 24 h (Mateos et al. 2007) and (b) several freeze-thaw cycles in the days prior to the failure when the rocky massif is partially saturated after a rainy period (Mateos et al. 2012).

The triggering conditions of Son Poc rockfall were analyzed based on the meteorological data recorded from different nearby weather stations (see location in Fig. 1): Biniforani Nou B249 (rainfall data), Bunyola-Raixa B260 (rainfall data), and B236C Palma-Universidad (temperature data). The data acquired were the following: daily precipitation (mm), accumulated rainfall (mm), and minimum temperatures (°C) recorded from the beginning of February 2013. Figure 4 shows the graph that relates all these parameters to the occurrence of the Son Poc rockfall. This graph reveals that the rockfall took place after a rainy period, with accumulated rainfall up to 85 mm/34 days, according to the nearest weather station (B249), and very clearly in a cold period, when the temperature hovered at around 0 °C with six freeze-thaw cycles in the 34 days prior to the failure, and with minimum values up to −5.14 °C on the 27th of February 2013.

More than likely, the Son Poc rockfall took place because of the cumulative effect of the freeze-thaw cycles, which weaken the rock and propagate fissures. Some researchers believe that the frequency of rockfalls seems to be regulated by thermal fluctuations around 0 °C (Frayssines and Hantz 2006; Wieczorek and Jäger 1996; Shihi et al. 2004), as in the present case, and that the phenomenon of gelifraction is intensified as the frequency of temperature changes rises, while the absolute value of the thermal oscillation bears little influence (Mateos et al. 2012).

Three-dimensional simulation

Son Poc rockfall event has been simulated using RocPro3D software (www.rocpro3d.com). The input digital elevation model (DTM) was generated by the National Geographic Institute (www.ign.es) at a resolution of 5 m×5 m. According to field observations and the available geological map (Mateos 2002), four lithological units have been differentiated (Fig. 5b), being (a) hard rocks corresponding to the Liassic dolostones, (b) soft rocks corresponding to the Raethiense marly limestone, (c) soft soil corresponding to the alluvial deposits, and (d) hard soil from the road pavements. The calibration of the parameters for every unit cell (coefficients R_N and R_T, threshold angle β_{lim}, and friction coefficient k) was based on the available numerical codes provided by RocPro3D (existing default soils) and others softwares (CRSP, RocFall, STONE), the parameters values found in the literature (Azzoni et al. 1992; Hungr and Evans 1988), and field observations, such as the presence of boulders and rock deposit, the runout distance, the propagation areas, and the location of impacts (Fig. 5, Table 1). The rockfall source area (110 m^2) was located at the cliff crowning the Son Poc peak based on field work observations. This source area was used to release 150 rock blocks, calculating their energy, velocity, height, density, and impact information for every trajectory (Fig. 7). Note that the considered volume for these blocks was 8 m^3, being the average size of the blocks hitting the houses (Fig. 3f). The shape of blocks for the simulation is defined as a sphere with diameter of 2.5 m. A grid of 500×500 cells was set for the envelope calculation.

The computed trajectories evidence two chutes that concentrate most of the blocks (Fig. 6): one oriented southeast (SE), which coincides with most of the mapped boulders, and the other one oriented SW that concentrates fewer mapped boulders. In addition to rock block trajectories, estimated velocity and energy of falling blocks are the most relevant results for the design of counter measurements. Trajectories with energy values greater than 15,000 kJ and peak velocities up to 57 m/s are concentrated in the middle part of the SE chute, whereas in the SW chute, both the energy and the velocity estimates are lower (Fig. 7). The bounce heights of simulated rockfall trajectories fall within the range of 1 to 15 m, being smaller close to the source area and increasing downslope where energy and velocity increase. However, the highest bounces are estimated in the SW chute (up to 15 m) rather than in the SE chute (1 to 6 m), as it occurs for energy and velocity estimates. This is probably due to the topographic control on the SW chute that makes the runout zone shorter and the spreading of the trajectories thinner.

The density map provides the percentage of trajectories that cross each cell of the grid. In Son Poc, the highest density is located in the SW chute. However, in the SE chute, high densities closer to a channel can be observed. Overall, the number of impacts and

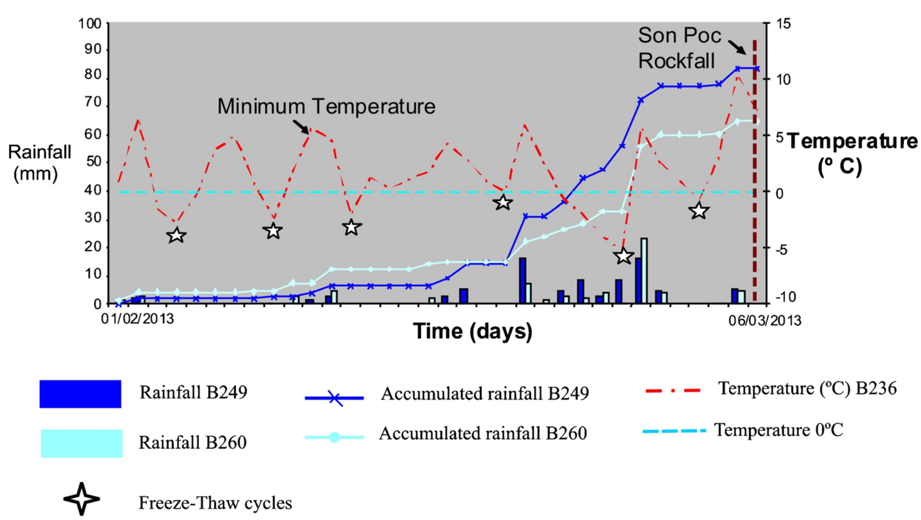


Fig. 4 Relationship between daily rainfall, accumulated rainfall, and minimum temperatures recorded at the nearest weather stations: B249, B260, and B236 (see location in Fig. 1). The Son Poc rockfall took place because of the cumulative effect of numerous freeze-thaw cycles prior to the failure

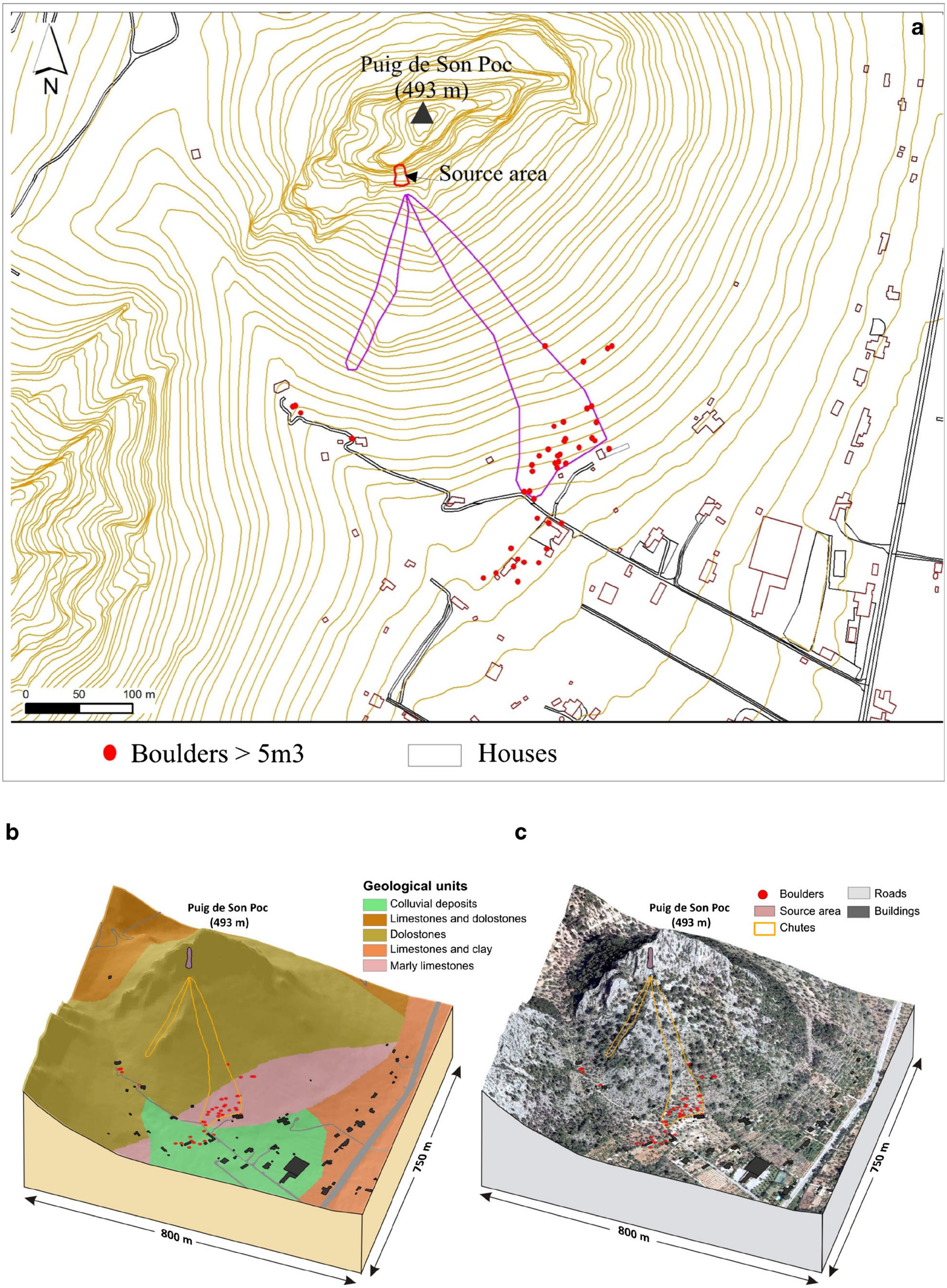


Fig. 5 **a** Boulders inventory and chutes observed on the field over the topographical map. **b** Geological map based on Mateos (2002). **c** Son Poc rockfall main spatial features over an ortho-image

Table 1 Input parameters for the lithological groups identified in Son Poc study area

Parameters	Dolostones	Marly limestone	Colluvial deposits	Roads
Restitution coefficients				
Mean normal value, μ_R_N [–]	0.75	0.65	0.45	0.42
Mean tangential value, μ_R_T [–]	0.85	0.75	0.7	0.87
Standard deviation, σ_R [–]	0.011	0.0125	0.012	0.012
Limit velocity, V_R (lim) [m/s]	10	10	10	10
Limit standard deviation, σ_R (lim) [–]	0.005	0.0075	0.006	0.004
Lateral deviation				
Standard deviation, $\sigma\_\theta h$ [–]	10	8	5.5	8
Limit velocity, $V\_\theta h$ (lim) [m/s]	10	10	10	10
Limit standard deviation, $\sigma\_\theta h$ (lim) [–]	5	4	2.75	4
Rebound flattening				
Standard deviation, $\sigma\_\theta v$ [°]	1	1	1	1
Limit velocity, $V\_\theta v$ (lim) [m/s]	10	10	10	10
Limit standard deviation, $\sigma\_\theta h$ (lim) [–]	2	2	2	2
Friction coefficient: sliding (lumped mass) or rolling (rigid block)				
Mean value, μ_k [–]	0.4	0.5	0.8	0.6
Standard deviation, σ_k [–]	0.04	0.045	0.045	0.04
Limit velocity, V_k (lim) [m/s]	10	10	10	10
Limit standard deviation, σ_k (lim) [–]	0.03	0.03	0.03	0.03
Transition parameters				
Angle β_lim (acute case) [°]	4	3	6	4
Angle β_lim′ (obtuse case) [°]	35	35	45	35

stopping points are in agreement with both chutes and field observations. Being the stopping points related to the runout distance, it is observed that for the SW chute, the model runout distance slightly overpasses the mapped boulders, whereas for the SE chute, the calculated runout distance is not large enough for several boulders. That is probably due to the size of modeled

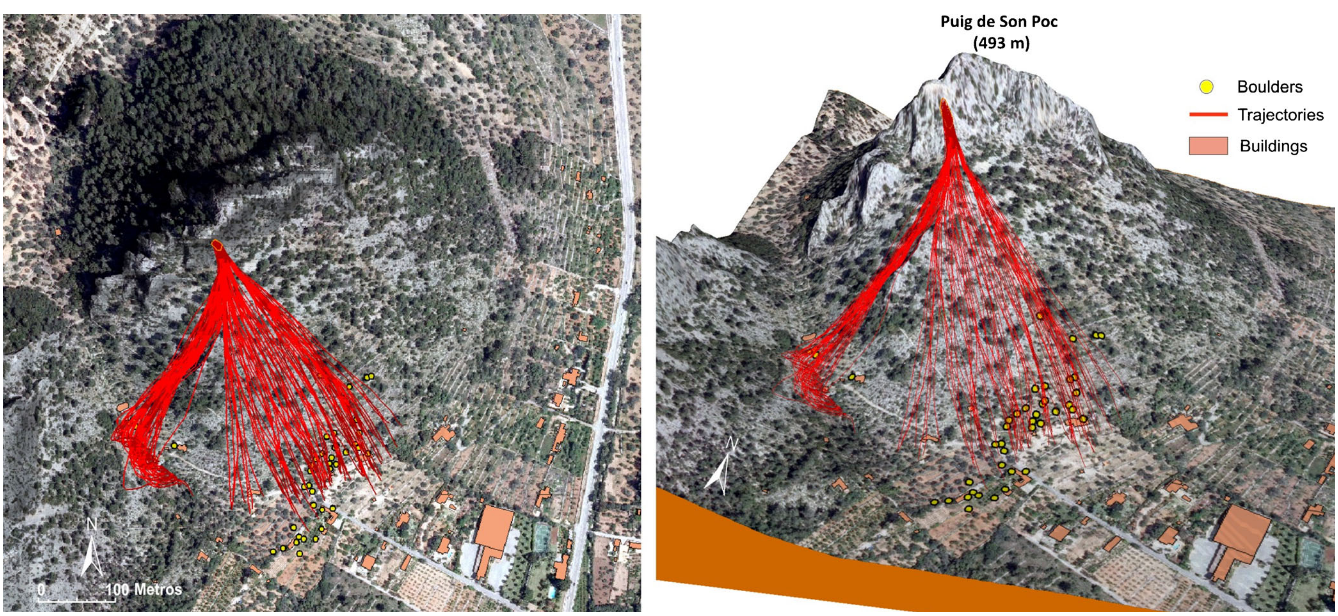


Fig. 6 Computed trajectories by RocPro3D

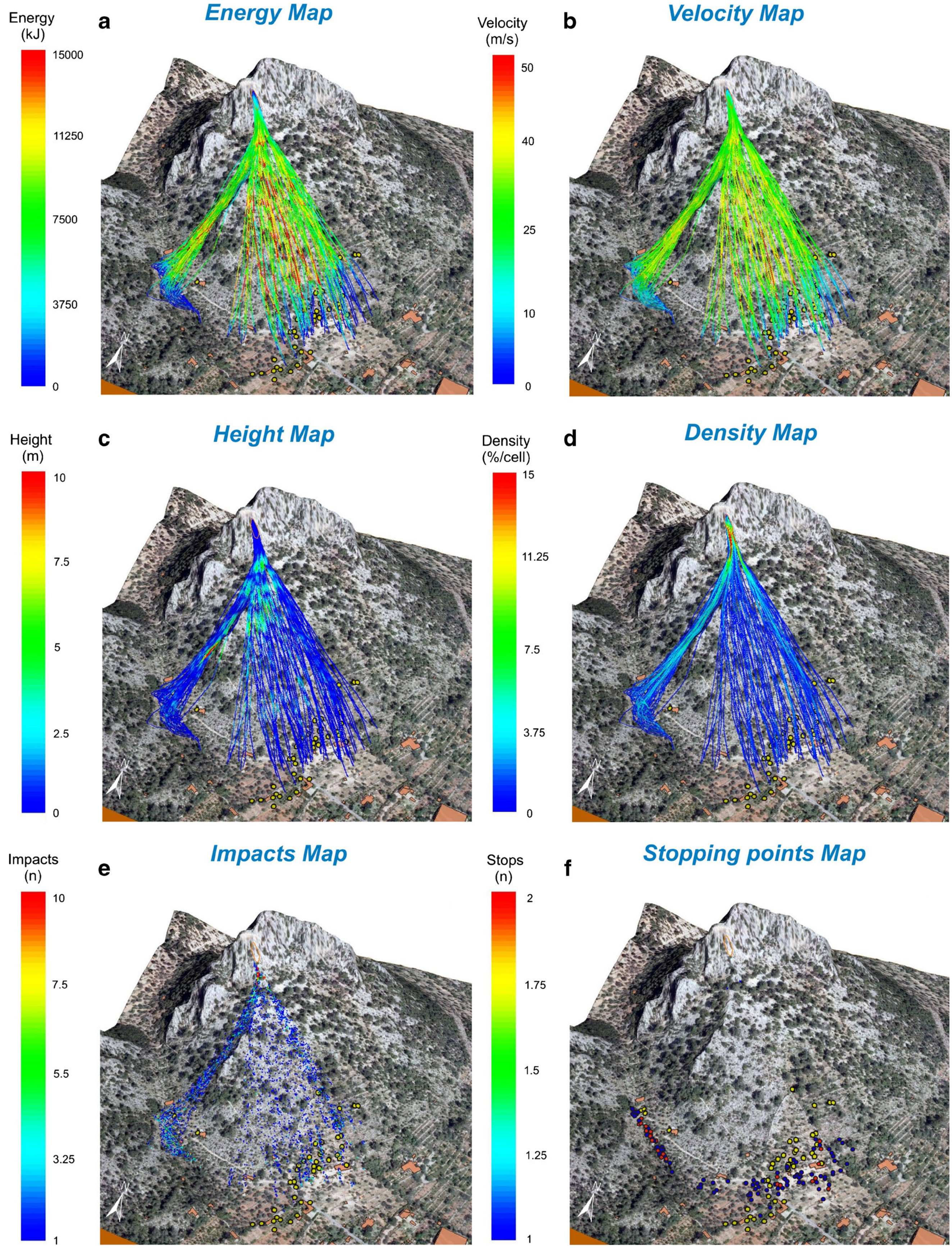


Fig. 7 a Energy map. b Velocity map. c Bounce height map. d Density map. e Impact points map. f Stopping points map

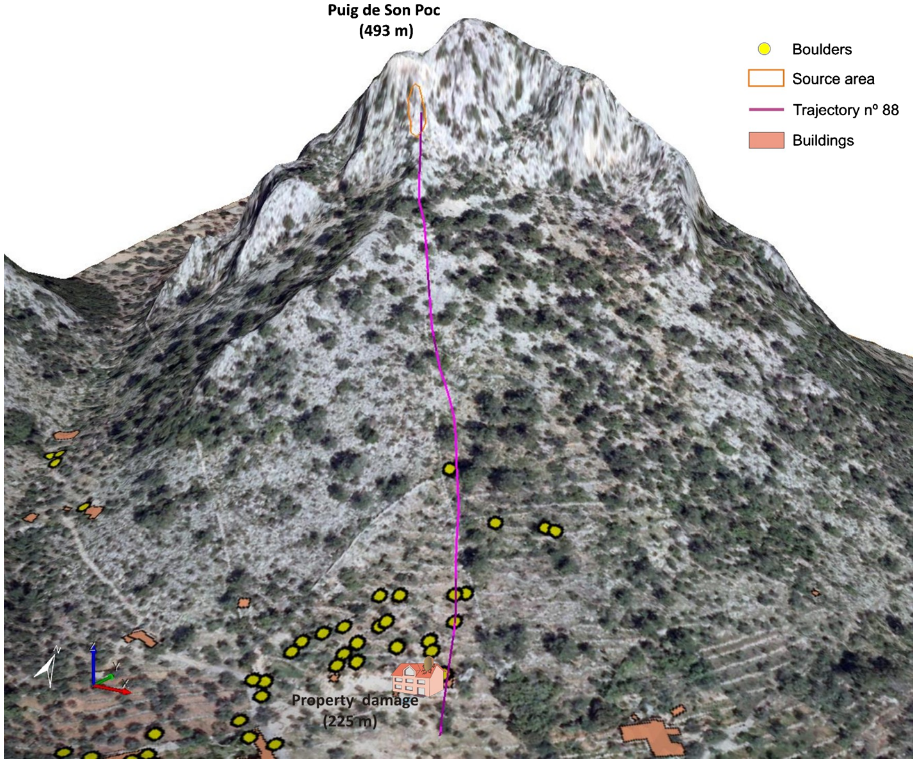


Fig. 8 Display of the selected trajectory (no. 88) which crashed into the house (see Fig. 3f)

blocks (8 m^3) that does not take into account the whole range of inventoried block volumes (1 to 35 m^3).

In order to simulate the trajectory of the 8-m^3 boulder that crashed into the house through the rear wall and the roof, the most similar trajectory has been selected from the whole amount of 150 rock block simulations (Fig. 8). Figure 9 reveals different profile views and graph views of this trajectory, analyzing the velocity, energy, and height. Analyzing the energy, velocity, and height profiles of this trajectory (Fig. 9) permits to determine that the rock block hit the house with a decreased energy (3,000 kJ) and a decreased velocity (12 m/s), being the lowest possible bounce height (0.5 to 1 m). These results suggest that, at this point of the trajectory, the rock block was rolling and maybe even sliding along the slope, as it can be appreciated from the scars left from Fig. 3c and f.

Discussion and conclusions

The Son Poc rockfall occurred on the 6th of March 2013. The field work carried out by aerial and in situ reconnaissance allowed us to identify the rockfall mechanism and to localize detached boulders as well as the two main chutes where boulders bounced and rolled along the slope. Toppling was the rockfall mechanism detaching 4.000 m^3 of the Jurassic dolostone cliff formed by vertical strata. The impact of these rocks into the slope produced their fragmentation into boulders, ranging from 1 to 35 m^3 in volume. Two main chutes were identified: one of them extended 376 m towards the southeast (SE) and the other extended 150 m towards the southwest (SW). The boulders stopping points are located at the foot of the slope, where several of them produced damages to houses and gardening zones.

The triggering conditions of Son Poc rockfall were analyzed based on the meteorological data recorded from different nearby weather stations. According to this analysis, the rockfall took place after 85 mm of cumulated rainfall and six freeze-thaw cycles in 34 days prior to the failure. More than likely, the combination of intense rainfall and cumulative freeze-thaw cycles weakened the rock through gelifraction and propagated fissures. This explanation is in agreement with the hypothesis demonstrated by Mateos et al. (2012) relating to numerous rockfall events produced between 2008 and 2010 in the Tramuntana Range, when the island experienced the coldest and wettest winters of the past 40 years.

Son Poc rockfall simulation through RocPro3D was useful to reproduce the dynamic of this event, which is in agreement with field observations. The computed trajectories reveal both SE- and SW-oriented chutes, with the SE chute being the one that concentrates greater energy values (up to 15,000 kJ) and peak velocities (up to 57 m/s), and the SW chute being the one with greater bounce heights (up to 15 m) and trajectory density. Overall, a number of impacts and stopping points are in agreement with field observations, even though slight differences are appreciated for certain boulders. This is probably due to the size of modeled blocks, which is unique (8 m^3) and does not reproduce the whole range of inventoried block volumes. However, there is a very good accuracy between the simulated trajectory of the 8-m^3 boulder that crashed into the house through the rear wall and the roof. The simulation reveals that the impact was produced with 3,000 kJ at 12 m/s and rolling or even sliding along the slope (bounce height, 0.5 to 1 m). Fortunately, no fatalities occurred despite of some people were on the area.

RocPro3D software has resulted to be a very good tool to reproduce rockfall events on this region. However, some limitations regarding this case study were identified relating to the type of movement and soil/block parameters. RocPro3D could not show with accuracy the

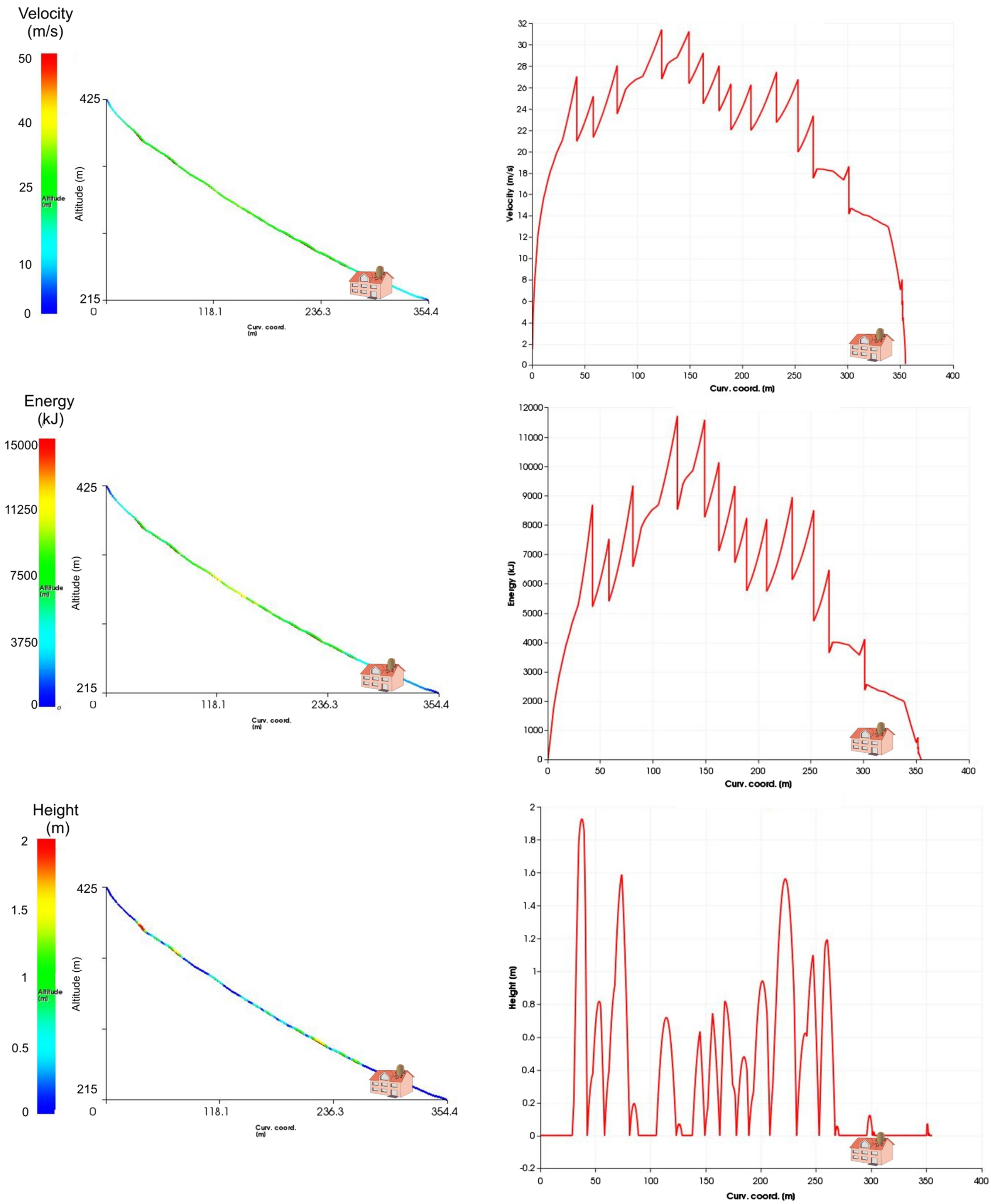


Fig. 9 Profile views and graph views of the trajectory number 88 which crashed into the house

toppling movement because it is three-dimensional software for trajectography modeling of rockfalls. In this sense, numerical model does not allow to introduce parameters such as the orientation of joints. For this, the proposed simulation should be also considered and applied in other rockfall hazardous areas on the Tramuntana Range, permitting to assess the risk of exposed urban settlements and to design protective works.

Acknowledgments

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