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REFERENCE DOCUMENTS

DR-1	Annex I - Description of Work of DORIS – "Ground Deformations Risk Scenarios: an Advanced Assessment Service"
DR-2	Deliverable 5.1- Large scale thematic maps for selected test-sites (1:50.000)

List of Acronyms and Abbreviations

ALTAMIRA	Altamira Information
CA	Consortium Agreement
CNR	Consiglio Nazionale delle Ricerche
CP	Civil Protection
DAP	Data Access Portfolio
DInSAR	Differential Synthetic Aperture Radar Interferometry
DOW	Description of Work
DPC	Dipartimento della Protezione Civile
EC	European Commission
ELGI	Magyar Allami Eotvos Lorand Geofizikai Intezet
EO	Earth Observation
ERCS	Emergency Response Core Service
ERS	Emergency Response Service
ESA	European Space Agency
EU	European Union
EUAC	External User Advisory Committee
FOEN	Bundesamt fuer Umwelt
FP	Focal Point
FP7	7th Framework Programme
FTS	Fast Track Service
GAMMA	Gamma Remote Sensing Research and Consulting
GMES	Global Monitoring for Environment and Security
IGME	Instituto Geológico y Minero De España
INSPIRE	Infrastructure for Spatial Information in Europe
IT	Information Technology
NFP	National Focal Point
PGI	Panstwowy Instytut Geologiczny - Panstwowy Instytut Badawczy
R&D	Research and Development
SAFER	Services and Application For Emergency Response
TRE	Tele-Rilevamento Europa
UNIFI	Università degli Studi di Firenze
WP	Work Package

EXECUTIVE SUMMARY

In this document we describe the occurrence of 67 mass movements in the Tramuntana Range recorded during the period 2008-2010 an exceptional event in the history of the island as there is no evidence in the historical record (since the 17th Century) of any similar event.

TABLE OF CONTENTS

1. INTRODUCTION

The island of Majorca has a variety of different geomorphological domains, most prominently the Tramuntana Range in the norhwestern part of the island. The steep topography of this chain, which is linked to its geological complexity and Mediterranean climate, determines intense slope dynamics. During the hydrological years 2008 to 2010, Majorca experienced one of the coldest and wettest winters in living memory. Not only the accumulated rainfall showed twice the average recorded values, this period also witnessed the highest rates of intense rainfall (up to 296 mm/24h) since instrumental records have been available (1944). These rainy episodes have also coincided with cold periods in which several days elapsed with temperatures around 0º C and minima up to -6.8º C (250 m a.s.l.), anomalous values in the mild Mediterranean climate. The result was that 67 mass movements were triggered, distributed along the Tramuntana Range, namely 48 rockfalls, 1 rock avalanche, 15 landslides and 3 karstic collapse.

The mass-movement inventory covering this period was carried out with the support from the Emergency and Road Maintenance Services, which informed us of every occurrence us such, and most of the movements were dated. Others were reported by private individuals, and the remaining cases were located during two helicopter flights over the range.

2. Landslide event 2008-2010

Rockfalls

The distribution of these movements shows that both the northern and the southern face were affected. Table 1 shows the characteristics of some of the rockfalls and figure 1 shows the photographs of some of the most important. The largest rockfall was at Son Cocó (inventory number 30008), which involves a volume of 300,000 m^3, and it was classified as a rock avalanche (Mateos et al., 2010).
All the rockfalls have affected practically vertical rock scarps made up of Liassic limestone, located at altitudes between 250 and 700 m. On the northern face, the rockfalls took place through planar failures, with the predominant direction being N30ºE, which coincides with the direction of the thrust fronts in the Range. On the southern face, the failure model is a wedge type, with two main failure planes – N30ºE and N110ºE– that mark the fracture pattern of the mountain range on this face (Gelabert, 1198).

The runout of the rockfalls that took place on the southern face was longer than those on the northern face, due to the layout of the materials on the slopes. Thus, on the southern face, rockfalls took place on vertical rock massifs of Liassic limestone which overlie the softer materials from the Rhaetian (Upper Triassic), made up of dolomites and marls. The latter give rise to less rugged slopes with angles around 30º, which allow the blocks to move and roll. However, on the northern face, the thrusts give rise to very vertical fronts that define the slope, and the blocks accumulate at the foot with a lower horizontal component to the movement.

Landslides

Landslides are small to medium-sized movements that affect clays with gypsum and volcanic rocks dating to the Late Triassic (Keuper). Keuper outcroppings are predominantly on the northern face, linked to the detaching surfaces of the thrusts. They are fine-grained soils with low to medium plasticity, with effective cohesion values of around 0.4 Kp/cm^2 and very low permeability values of around $1.8x10^{-6}$ cm/s (Mateos et al., 2003; Mateos et al., 2009). The landslides were mainly located on the northern face of the Tramuntana and they tend to be complex rotational landslides with mudflows at the bottom, that affected roadside-slopes with steep inclines (>30º); in some cases they are reactivations of previous movements (Sa Calobra and Banyalbufar). Table 2 shows the characteristics of some of the landslides during the rainy period, and the figure 2 shows some photographs of the most important ones. They all affected the road network in the mountain range, primarily the Ma-10 road. The Estellencs landslide (Fig. 2-3) on the 8 March 2010 kept this road closed for three months, triggering numerous economic losses in the towns of Estellencs and Banyalbufar.

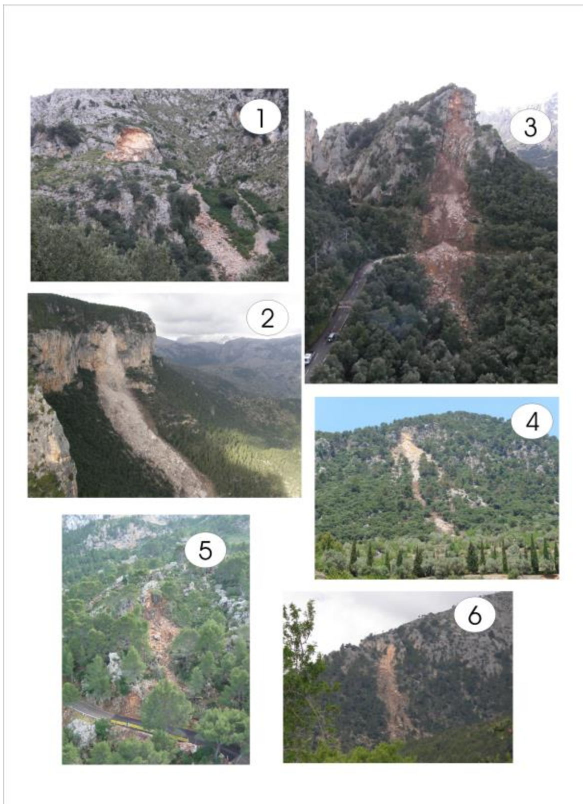

Figure 1 Photographs of the most important dated rockfalls. 1) Puig Tomir (27/11/2008), 2) Son Cocó (19/12/2008), 3) Gorg Blau (31/12/2008), 4) Biniforani (5/01/2009), 5) Estellencs (15/01/2010) and 6) Son Antic (17/02/2010). The Gorg Blau rockfall cut off the Ma-10 road for 4 months.

Figure 2 Photographs of the most important landslides recorded that affected the road network in the mountain range. 1) Sa Calobra (3/12/2008), 2) Cala Tuent (15/12/2008), 3) Estellencs (8/3/2010) and 4) Banyalbufar (9/5/2010). The Estellencs landslide cut off the Ma-10 road for 3 months.

Table 1. Characteristics of the rockfalls dated during the period from October 2008 to February 2010

Rockfall Inventory No.	Date	Face	Volume (m^3)	Altitude of failed massif (m)	Runout (m)	Type of failure (failure plane orientations)	Lithology
Puig Tomir Nº 30003	27/11/2008	N	16,000	620	350	Planar N30ºE	Liassic limestone
Son Cocó Nº 30008	19/12/2008	S	300,000	700	650	Wedge N30ºE N90ºE	Liassic limestone
Gorg Blau Nº 30009	31/12/2008	N	30,000	600	450	Wedge N30ºE N120ºE	Liassic limestone
Biniforani Nº 30013	5/01/2009	S	28,000	650	350	Wedge N30ºE N110ºE	Liassic limestone
Biniaraix Nº 30014	6/01/2009	N	3	600	100	planar N70ºE	Liassic limestone
Port de Valldemossa Nº 30015	07/01/2009	N	8	340	20	¿?	Liassic limestone
Son Alberti Nº 30018	23/01/2009	N	10	200	5	-	Liassic limestone
Casa Puigpunyent 30020	14/09/2009	N	2	360	150	Wedge N120ºE N30ºE	Liassic limestone
Estellencs Nº 30021	15/01/2010	N	10,000	350	50	Planar N110ºE	Liassic limestone
Son Antic Nº 30030	17/02/2010	S	14,000	350	250	Wedge N120º E N30ºE	Liassic limestone
Son Bunyola Nº 30031	19/02/2010	N	10	250	20	Planar N30ºE	Liassic limestone

3. GEOLOGICAL STRUCTURE FACTORS

Practically all the slope movements recorded on Majorca had place in the Tramuntana Range. The variety of lithologies cropping out in this mountain chain determines a wide range of slope movements.

The Tramuntana Range correspond to the reliefs caused by the Miocenic structuring linked to the Alpine fold, formed by a series of NW overlapping thrusts (Gelabert et al., 1992; Gelabert, 1998). The stratigraphy of the mountains begins with the deposits of siliceous sandstone from the Buntsandstein (Lower Triassic) until the more recent colluvial sediments from the Quaternary. Carbonated lithologies clearly predominate and especially Jurassic limestone and dolostone, which constitute the framework of the mountains. The NE-SW mountain alignments correspond to the overlapping system, and the regional detachment level are the Later Triassic (Keuper) sediments (Alvaro, 1987), clay and gypsum with volcanic rock. The oldest materials in the range outcrop

on the coastal strip, in the southwest sector. These materials are predominantly soft, in contrast to the hard rocks that prevail in the rest of the range. The geological structure of mountain chain tends to determine the layout of outcroppings, the distribution of slopes and particularly the presence of faults and discontinuities that often determine the planes and failure surfaces of the movements. The northern face is more hazardous due to the existence of steeper slopes and a higher presence of outcroppings of soft materials; both of these factors are conditioned by the NW-overlapping thrusts and the regional tectonics.
Landslides and mud-earth flows are frequent phenomena, primarily affecting the soft sediments from the Late Triassic (Keuper), made up of clays with gypsum, as well as an entire series of loamy materials from the Paleogene and Neogene that occasionally outcrop along the mountain range. Rockfalls are the most frequent slope movements in the Tramunana Range due to the predominance of Jurassic rocky massifs made up of limestone and dolostone.

Table 2. Characteristics of the landslides dated during the period from October 2008 to May 2010

Movement Date	Volume (m^3)	Altitude (m)	Typology (Cruden and Varnes, 1996)	Lithology	Slope
Costa Deià (nº 30002) 29 Oct 2008	1,500	80	debris flow	colluvial deposits Quaternary	45º
Sa Calobra (nº 30004) 3 Dec 2008	7,000	585	rotational landslide and earth flow	clays with gypsum from Keuper	40º
Cala Tuent (nº 30007) 15 Dec 2008	12,000	168	rotational landslide	clays with gypsum from Keuper	42º
Es Verger (nº 30005) 15 Dec 2008	200	410	debris flow	colluvial deposits Quaternary	50º
Edificio Siesta (nº 30017) 8 Jan 2009	100	158	debris flow	marls and calcareous sandstones Oligocene	90º
Estellencs (nº 30032) 8 Mar 2010	30,000	350	rotational landslide and earth flow	clays with gypsum from Keuper	30º
Petrol station (nº 30034) 9 Mar 2010	3,000	250	earth and debris flow	clays with gypsum from Keuper	35º
Banyalbufar (nº 30036) 9 May 2010	4,500	300	rotational landslide and earth flow	clays with gypsum from Keuper	45º

4. TRIGGERING FACTORS

Majorca has a typically Mediterranean climate, with mild winters and warm-dry summers. The maximum precipitation takes place during the autumn months due to the arrival of the first high cold air masses, which contrast with the high temperature retained by the sea. This phenomenon is known as "*gota fría*" (cold rain), in which heavy storms are accompanied by intense rainfall episodes (up to 250 mm in 24 hours). The orography of the range clearly controls the distribution of precipitation. The central

sector (Lluc) registers average annual precipitation of 1,200 mm, which gradually drops towards the extreme SW of the range (Calviá), where the average annual precipitation is less than 300 mm.
During the period spanning from October 2008 to May 2010, the island of Majorca experienced two of the coldest and rainiest winters in living memory, with accumulated rainfall being almost twice the average value. On the 15th of December 2008 the highest precipitation was registered in the central sector of the Tramuntana Range, since instrumental data has been available (1944). A total of 296 mm of rain fell in 24 hours near Sóller. Mateos et al. (2007) carried out a statistical analysis of intense rainfall in the area, which allowed to obtain the maximum 24-hour rainfall values for return periods of 5, 10, 25 and 100 years. The values obtained on the 15th of December 2008 are very similar to those calculated for the return period of 100 years, which reflects the uniqueness of this extreme precipitation record. However, the 2008-2010 period was not only exceptionally rainy on the island but also anomalously cold, with abundant snowfall as well as freezing in the highest zones in the range. The high precipitation and the low temperatures coincided, as the rainfall took place mainly during the winter months, linked to cold fronts coming in from northern Europe. During the last two winters, the majority of the weather stations in the range had registered temperatures oscillating around 0ºC, with minimum values as low as -6.8 ºC (500 m.a.s.l).

Rockfalls
Fig. 3 shows the graphs that relate the daily precipitation, accumulated rainfall and minimum temperatures recorded to the occurrence of the dated rockfalls. In order to obtain a general picture, the reference was the meteorological data from the B013-Lluc weather station (490 m a.s.l), located in the heart of the mountain range. As a general criterion, all the rockfalls took place after intense precipitations and very clearly in the coldest periods, when the temperature hovered at around 0º C. With the aim of carrying out a thorough analysis, Table 3 was drawn up, in which the following parameters were quantified for each rockfall, taking into account the meteorological data from the stations closest to the failure point: (1) maximum precipitation in 24 hours recorded in the ten days prior to the failure; (2) minimum temperature recorded in the ten days prior to the failure. To get these values, the temperature at the elevation of the rockfall scarp was estimated by applying a thermal gradient of -6.5ºC for each 1,000 metres (Mateos, 2007); (3) accumulated rainfall from the start of the rainy period until the moment of failure; and (4) number of freeze-thaw cycles that took place prior to the rockfall.
The analysis of these data reveals the following:

- Some of the rockfalls (~ 27%) took place after occurrences of intense rain >90 mm /24 h, regardless of the temperature..
- Most of the rockfalls started in saturated rocky massifs (accumulated rain >800 mm) when there were several freeze-thaw cycles in the days prior to the failure, regardless of whether the maximum daily rainfall were overly intense (around 30 mm).

Tab. 3 and fig. 3 provide an overview which enables us to establish that largest rockfalls were produced on rocky scarps located above 600 m, showing a clear relationship to freeze-thaw cycles prior to the failure. Minor rockfalls were caused on lower scarps, 250 m- 350 m, and were more closely related to episodes of moderate-intense rainfall.

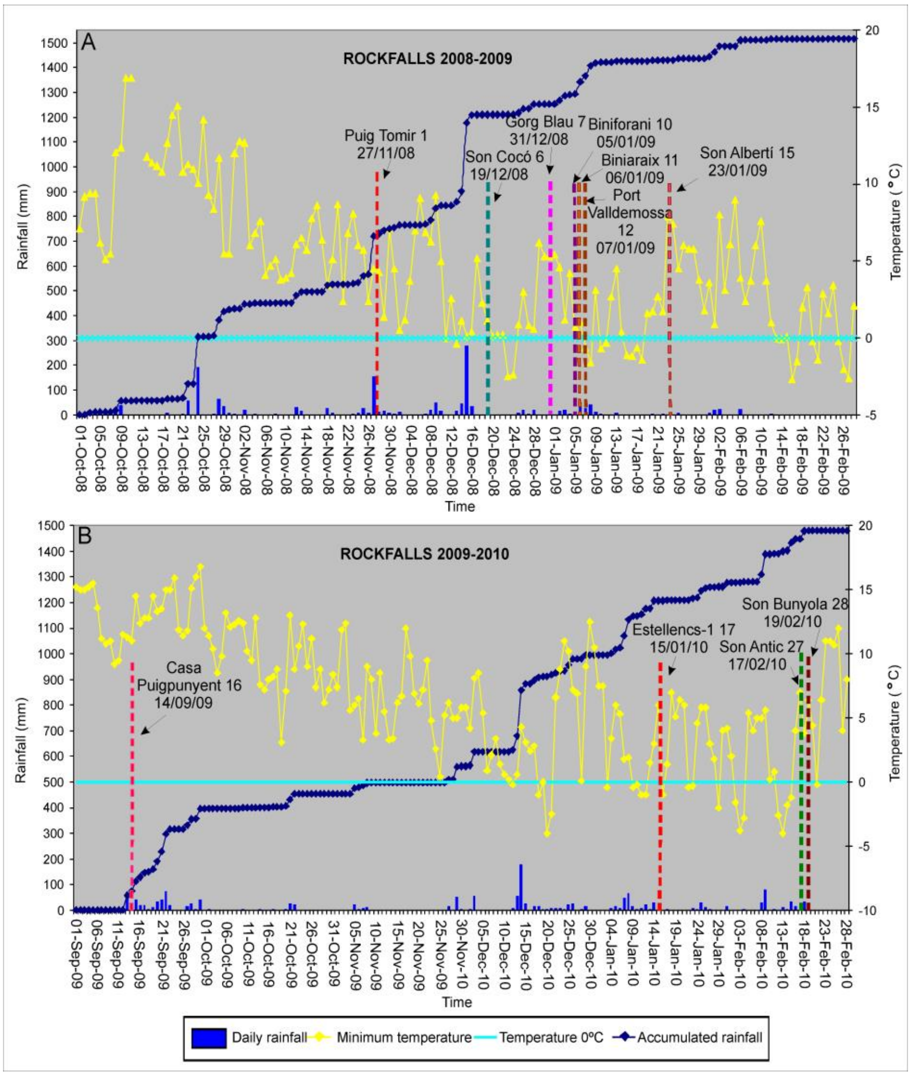

Figure 3 Relationship between daily rainfall, accumulated rainfall and minimum temperatures (recorded at the B013 Lluc weather station) and the occurrence of rockfalls in the periods a) October 2008-February 2009 and b) September 2009-March 2010

Landslides

Fig. 4 shows the relationships between the different meteorological parameters – daily rainfall, accumulated rainfall and minimum temperatures – and the occurrence of dated landslides. Once again B013-Lluc weather station was taken as the reference point. This overall picture reveals that the landslides recorded took place after episodes of moderate to extreme intense rainfall, with very high accumulated rainfall totals (> 800 mm). Bearing in mind the same parameters as the ones used for rockfalls, Tab. 4 was elaborated using the information from the weather stations located the closest to the movements. Some of the landslide were triggered after prior medium intensity rains, between 20 and 65 mm/24 h, and with very high accumulated rainfall figure (up to 1,000 mm); while others took place after very intense rainfall >120 mm/24 h, with values up to 190 mm/24 h in the case of the Sa Calobra landslide (inventory number 30004). This threshold coincides with that of 130 mm/24h estimated by Mateos et al. (2007) for historical landslides. However, unlike rockfalls, freeze-thaw cycles do not seem to trigger landslides and the altitude at which the movements took place is of no relevance.

Table 3 Values of the meteorological data related to the occurrence of rockfalls. For each case, the weather stations closest to the failure point were used

Rockfall Inventory No. date	Max. rainfall in 24/h (mm) (10 days prior to event)	Minimum temp. (ºC) (10 days prior to event)	Accumulated rainfall (mm)	No. of freeze-thaw cycles
Puig Tomir (Nº 30003) 27 Nov 08	128.5 (27 Nov 2008)	1.6 (26 Nov 2008)	843.3	0
Son Cocó (Nº 30008) 19 Dec 08	150.2 (15 Dec 2008)	-1.6 (11 Dec 2008)	874.2	3
Gorg Blau (Nº 30009) 31 Dec 08	35.1 (26 Dec 2008)	-3.2 (23 Dec 2008)	1,409.2	6
Biniforani (Nº 30013) 5 Jan 09	33.3 (26 Dec 2008)	-3.5 (05 Dec 2009)	931.7	8
Biniaraix (Nº 30014) 6 Jan 09	23.5 (06 Jan 2009)	-1.1 (05 Jan 2009)	953.6	5
Port Valldemossa (Nº 30015) 07 Jan 09	24.3 (07 Jan 2009)	-1.3 (07 Jan 2009)	892.3	4
Son Alberti (Nº 30018) 23 Jan 09	6.3 (13 Jan 2009)	5.13 (18 Jan 2009)	669.7	0
Puigpunyent (Nº 30020) 14 Sept 09	45.3 (14 Sept 2009)	12.69 (12 Sept 2009)	87.9 14 Sept 2009	0 Ligntning storm
Estellencs (Nº 30021) 15 Jan 10	93.1(12 Jan 2010)	2.3 (10 Jan 2010	789.3	0
Son Antic (Nº 30030) 17 Feb 10	28.6 (15 Feb 2010)	-1.5 (13 Feb 2010)	874.4	2
Son Bunyola (Nº 30031) 19 Feb 10	36.2 (12 Feb 2010)	-1.5 (13 Feb 2010)	790.4	2

Table 4 Values of the meteorological data related to the occurrence of landslides. For each case, the weather stations closest to the failure point were used.

Landslide Inventory No. Date	Max. rainfall in 24 h (mm) (10 days prior to event)	Minimum temp. (ºC) (10 days prior to event)	Accumulated rain (mm) Since the start of the season	No. of freeze-thaw cycles (10 days prior to event)
Costa Deià (Nº30002) 29 Oct 08	64 (28 Oct 2008)	10.21 (25 Oct 2008)	179.6	0
Sa Calobra (Nº30004) 03 Dec 08	190.2 (27 Nov 2008)	-0.1 (02 Dec 2008)	900.3	1
Cala Tuent (Nº 30007) 15 Dec 08	61.7 (14 Dec 2008)	1.7 (13 Dec 2008)	1,075.2	0
Es Verger (Nº30005) 15 Dec 08	178.3 (15 Dec 2008)	-0.3 (01 Dec 2008)	626.4	1
Edificio Siesta (Nº 30017) 08 Jan 09	26.5 (06 Jan 2009)	0.8 (08 Jan 2009)	718.2	0
Estellencs (Nº 30032) 08 Mar 10	44.5 (07 Mar 2010)	- 0.05 (07 Mar 2010)	864.5	1
Petrol station (Nº 30031) 09 Apr 10	20,2 (04 Apr 2010)	8,9 (08 Apr 2010)	927,6	0
Banyalbufar (Nº 30036) 09 May 10	120.3 (03 May 2010)	16.4 (08 May 2010)	1,220.7	0

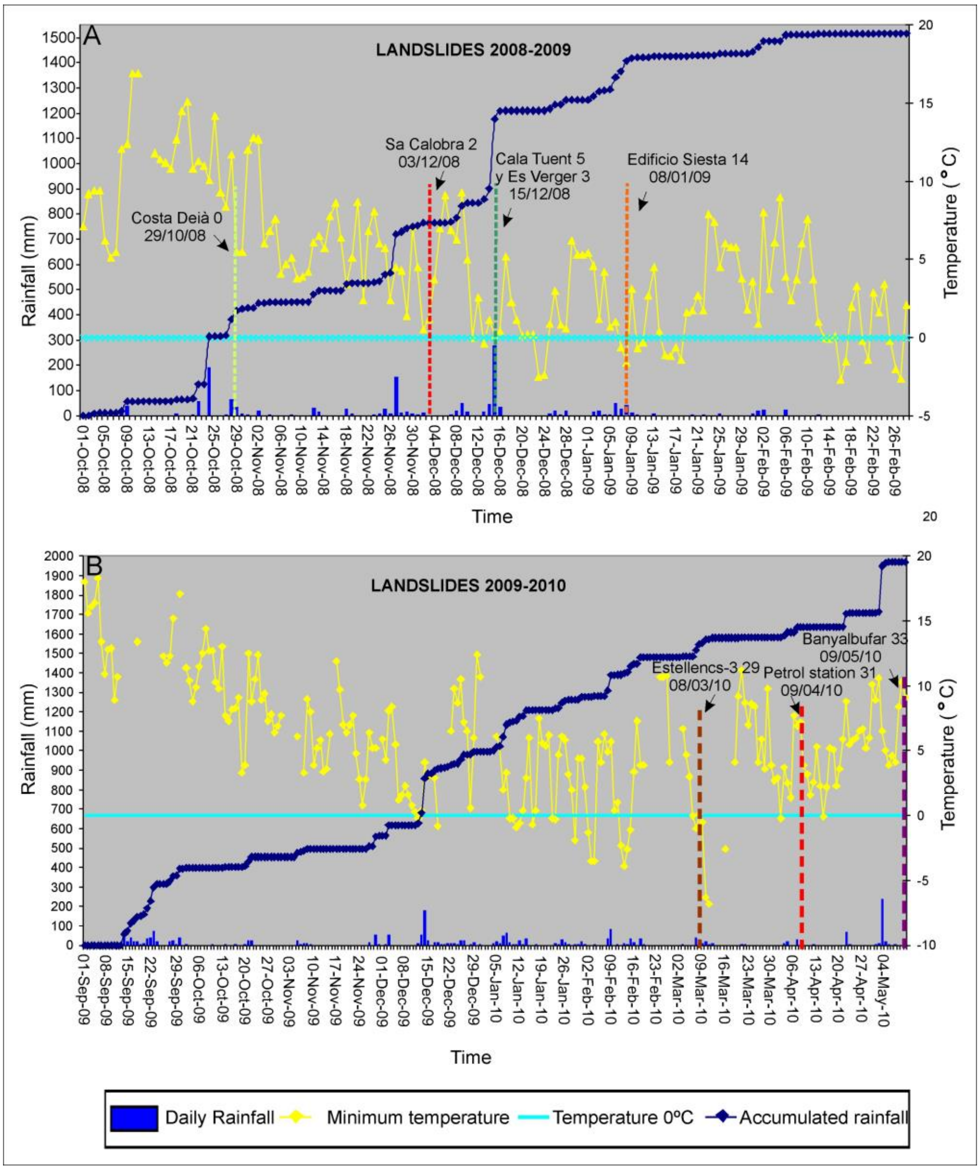

Figure 4 Relationship between the different meteorological parameters – daily rainfall, accumulated rainfall and minimum temperatures recorded – and the occurrence of landslides, taking B013-Lluc weather station as the point of reference. The landslides recorded took place after episodes of moderately to extremely intense rainfall, with high accumulated rainfall (> 850 mm)

5. EVENT 2008-20010 MAP

<table>
<tr><th colspan="3">Landslide event 2008-2010 map</th></tr>
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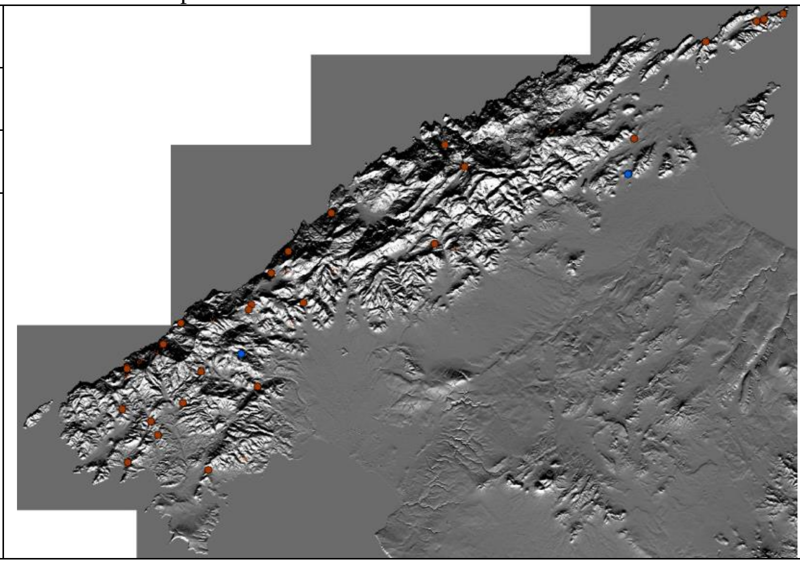
<tr><td>Date</td><td>September 2012</td><td rowspan="4"></td></tr>
<tr><td>Spatial Resolution</td><td>1:10.000</td></tr>
<tr><td>File Format</td><td>Esri shape file</td></tr>
<tr><td>Reference System (Geodetic System - Projection)</td><td>ERTS89 - UTM 31 N</td></tr>
<tr><td>Source:</td><td colspan="2">Working data generated from LANDSLIDE INVENTORY.</td></tr>
<tr><td>Description:</td><td colspan="2">Points, lines and polygons indicate the mass-movements recorded during the period 2008-2010 in the Tramuntana Range. It is an exceptional event in the history of the island as there is no evidence in the historical record (since the 17th Century) of any similar event.</td></tr>
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