



Debris flow triggering on Teide stratovolcano, Tenerife. A growing process?

Desencadenamiento de debris flow en el volcán Teide. ¿Un proceso creciente?

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Abstract

Mt. Teide is the highest mountain on Spanish territory (3,718 m.a.s.l.). It is a twin stratovolcano: Pico Viejo (3,100 m.a.s.l.) has a comparatively wide crater while the Pico del Teide crater itself, slightly to the east, last erupted possibly 1.2 ky BP (Lavas Negras). Below the modern lava flows, the Old Teide structure outcrops as a giant edifice; its most recent materials have been dated at 30 ky. The volcano shows very steep slopes (over 40°) with several prominent ravines, the most important being Corredor de La Bola and Corredor de La Corbata. The latter has been partially infilled by the Lavas Negras eruption. At its head there is a pale-coloured triangular area caused by intense fumarole weathering of phonolitic rocks. The fluvial activity of this ravine has not been relevant, there is a lack of references to it for at least the last 30 years. However, on September 22nd, 2010, heavy rain remobilized materials from the pale area (located at over 3,200 m.a.s.l.), causing an impressive debris flow. In the present paper we report the results of a morphometric, sedimentological and climatic study focusing on the unusual weather conditions that triggered this process, as a key to understanding other previous and future debris flows.

Key words: Debris flow; Teide volcano; heavy rains; tropical storm; Tenerife; Canary Islands.

Resumen

El volcán Teide es la montaña más elevada del territorio español, alcanzando los 3.718 m.s.n.m. Es un estratovolcán doble; el volcán de Pico Viejo (3.100 m.s.n.m) presenta un cráter amplio, mientras que el volcán Teide, en posición más oriental, tuvo su última erupción hace posiblemente 1,2 ka (Lavas Negras). Por debajo de



estos flujos lávicos recientes aflora la estructura del Teide Antiguo, un edificio gigante cuyos materiales más recientes han sido datados en 30 ka. Presenta laderas muy empinadas (por encima de 40°) y muestra algunos barrancos, siendo los más importantes el Corredor de La Bola y el Corredor de La Corbata. Este último ha sido parcialmente rellenado por las Lavas Negras. En su cabecera presenta una coloración pálida, con forma de triángulo, producida por una intensa alteración fumaroliana afectando a la roca fonolita. La actividad de este barranco no ha sido muy importante no existiendo referencias de ella para los últimos 30 años. Sin embargo, el 22 de septiembre de 2010 una lluvia intensa produjo la removilización de materiales desde la mancha pálida (localizada por encima de los 3.200 m.s.n.m.), formando un *debris flow* impresionante. En el presente artículo mostramos los resultados del estudio morfométrico, sedimentológico y climático, haciendo hincapié en las inusuales condiciones meteorológicas que produjeron el desencadenamiento de este proceso como clave para interpretar otros *debris flow* anteriores y prevenir el riesgo derivado de los futuros.

Palabras clave: *Debris flow*; volcán Teide; lluvias torrenciales; tormenta tropical; Tenerife; islas Canarias.

1. Introduction

Debris flows are typical deposits in arid and semiarid environments; they are a flow of sediments formed of mixed coarse and fine particles, water and air (Gutiérrez-Elorza, 2001). The water build-up necessary to cause such flows is provided by heavy rain or sudden melting of the snow cover. On this topic there is a wide literature (Innes, 1983; Costa, 1984 and 1988; Johnson and Rudine, 1984; Takahashi, 1991; Coussot and Meunier, 1996; Harvey, 1997;) referring to debris flows in high mountain zones (Berti *et al.*, 1999) and high latitudes (Rapp and Nyberg, 1981), and of course in volcanic areas (Palacios *et al.*, 1998 and 1999; Palacios, 1999; Zanchetta *et al.*, 2004; Ettlinger *et al.*, 2007). Some of the debris flows on Teide have already been described (Criado, 2006; Criado *et al.*, 2008; Rodríguez-González *et al.*, 2013).

The main aim of this paper focused in an event of debris flow happened on 22th September 2010 in the Corredor of La Corbata (Teide volcano, Tenerife, Fig. 1). In this case, the movement started when the amount of water mixed with fine particles produced by the fumaroles weathering and debris from Lavas Negras, produced a drop in viscosity and shear resistance (Johnson, 1970).

The objectives of this research are the precise characterization of the phenomena —ba-

sed in morphometrical and sedimentological study of the debris flow—, together with a detailed study of the weather conditions responsible for its genesis, to get the key to understand these processes in the Late Holocene evolution of Teide and its implication in the formation of some alluvial fans and also to implement the surveillance of debris flow as a natural hazard able to risk people and infrastructure.

2. Geomorphological and climate frameworks

Teide volcano complex, located on the island of Tenerife (Fig. 1), rises from 2,000 m high on its northern face and from 2,300 m on the southern face, reaching around 3,500 m high (Fig. 2), where there is a small plateau from which the terminal cone rises further to 3,718 m.a.s.l. It is a high altitude environment, which explains the climatic features of this mountain sector of Tenerife. The slopes are very steep, with gradients from 30° to 40°, rising continuously to a height of 1,500 m above the surrounding cirque floor. The present volcanic edifice started to build up 198 ky ago, with a large volume of basaltic lava flows. From 115 to 30 ky BP, Teide kept growing, but the rate of issue was progressively more moderate (Carracedo *et al.*, 2003) and the magma increasingly differentiated, ranging from basalts to phonotephrite (Carra-

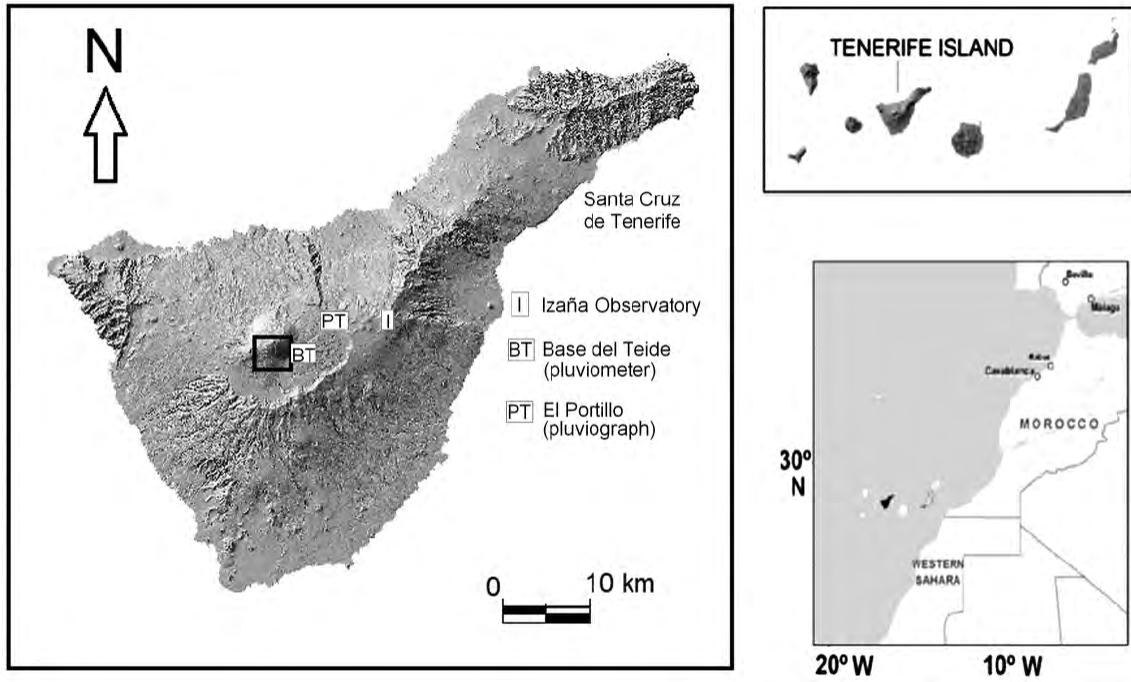


Figure 1. Location of the studied phenomenon on Tenerife Island.
 Figura 1. Localización del fenómeno estudiado en la isla de Tenerife.

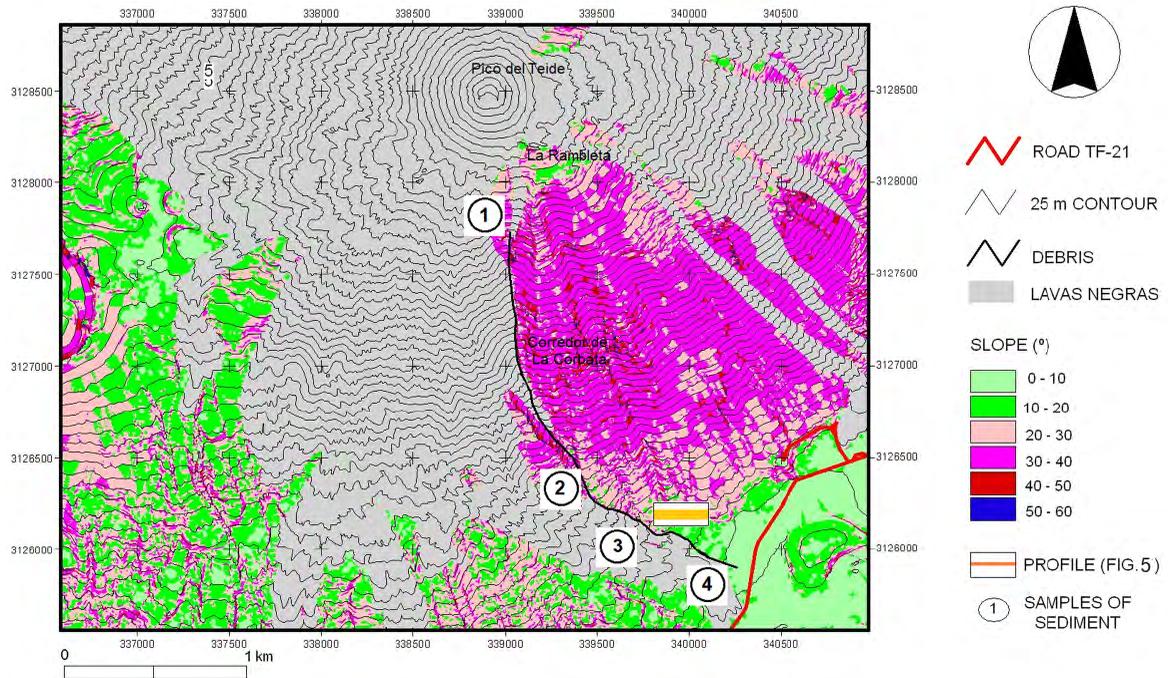


Figure 2. The debris flow of 22nd September 2010. Samples 1, 2, 3 and 4 were analyzed in this research.
 Figura 2. El debris flow del 22 de septiembre de 2010. 1, 2, 3 y 4 son las muestras analizadas en esta investigación.

cedo, 2006). The terminal cone was formed during the more recent eruption with phonolite composition (Carracedo, 2006; Carracedo *et al.*, 2003, 2007, 2013). Even today, in the small summit crater of the volcano there is a fumarole field with emissions of H₂O, CO₂, H₂S and SO₂ (Carracedo and Soler, 1983), which have produced considerable weathering of the rocky outcrops. Most of the whole central volcanic cone is covered by Lavas Negras (Fig. 2) issued during the last eruption, dated in XV Century AD by palaeomagnetism (Soler *et al.*, 1984; Soler and Carracedo, 1986) and at 1150±140 BP using ¹⁴C (Carracedo, 2006; Carracedo *et al.*, 2003, 2007, 2013). Eroded outcrops remain in the areas free from this recent lava layer, mainly on the southern slope, notably the ravines called Corredor de La Bola and Corredor de *La Corbata* (Martínez de Pisón and Quirantes, 1981; Bravo and Bravo-Bethencourt, 1989; Criado, 2006; Criado *et al.*, 2008; Rodríguez-González *et al.*, 2013).

The debris described in the present study is located within the Corredor de La Corbata (c. 100 m deep), extending from 3,350 m down to 2,285 m.a.s.l. and involving an area of 0.74 km² (Table 1). This ravine was largely formed between 30 ky and 1.2 ky ago, because it is partially infilled by Lavas Negras (Fig. 2).

Area of ravine (km ²)	0.74
Maximum height (m)	3,350
Minimum height (m)	2,285
Mean slope of basin (o)	30-40
Length of debris flow (m)	2,505
Volume (m ³)	~30,000
Mean slope of debris flow (o)	30-40

Table 1. Morphometry of debris flow on 22nd September 2010.

Tabla 1. Morfometría del debris flow del 22 de septiembre de 2010.

The morphogenetic activity of this ravine is weak nowadays, although alluvial fans are well developed at its foot, one of them (Cañada Blanca) reaches more than 3 km in length. A detailed survey showed abundant archaeological remains (pottery, stone wall

remnants of huts, and lithic artifacts) from the Guanche culture, spread sparsely over the several debris flows. A goat bone located in hut sites provided a ¹⁴C dating in 910±30 BP (Beta-330031). So we can suppose that most of that debris flow was deposited before the XVI century AD, since from then onwards the Guanche culture was progressively absorbed by their European conquerors.

In the eastern sector of the base of Teide, the alluvial fans overlapped lava flows from phase VIII of the Montaña Blanca dome (Carracedo, 2006), dated at 2 ky BP (Ablay *et al.*, 1995). These are in turn covered in some places by the Lavas Negras flows. To the west, the same lava flow covered debris flows in the proximal sector of the Cañada Blanca alluvial fan (Criado *et al.*, 2008; Rodríguez-González *et al.*, 2013). Therefore, the most important processes of alluvial-fan formation appear to be old, since only a few *levées* rich in stones and blocks without archaeological remains have been dated as after XVI century AD (Fig. 3).

Today close to the mouth of both corridors there is a cable-car, operating since 1971 and used by a big number of people.

On the other hand, the climate of the Canary Islands is characterized by atmospheric stability with a very low number of rainy days per year. However, events of strong instability may occur in short space and time scales. The significant reliefs of the islands create important pluviometric differences both in terms of total annual rainfall as in the intensity of individual events, with remarkable geographical contrast (Mayer *et al.*, 2017). In this context the high Canary summits and, consequently, the Teide National Park have singular features that make them different from other areas located at mid and low elevations where the population is concentrated.

Atmospheric stability is the usual climatic regime in Teide National Park. Due to the altitude (over 2,000 m.a.s.l.) being higher than the thermal inversion above the prevailing NE trade-winds, the area is affected most of the

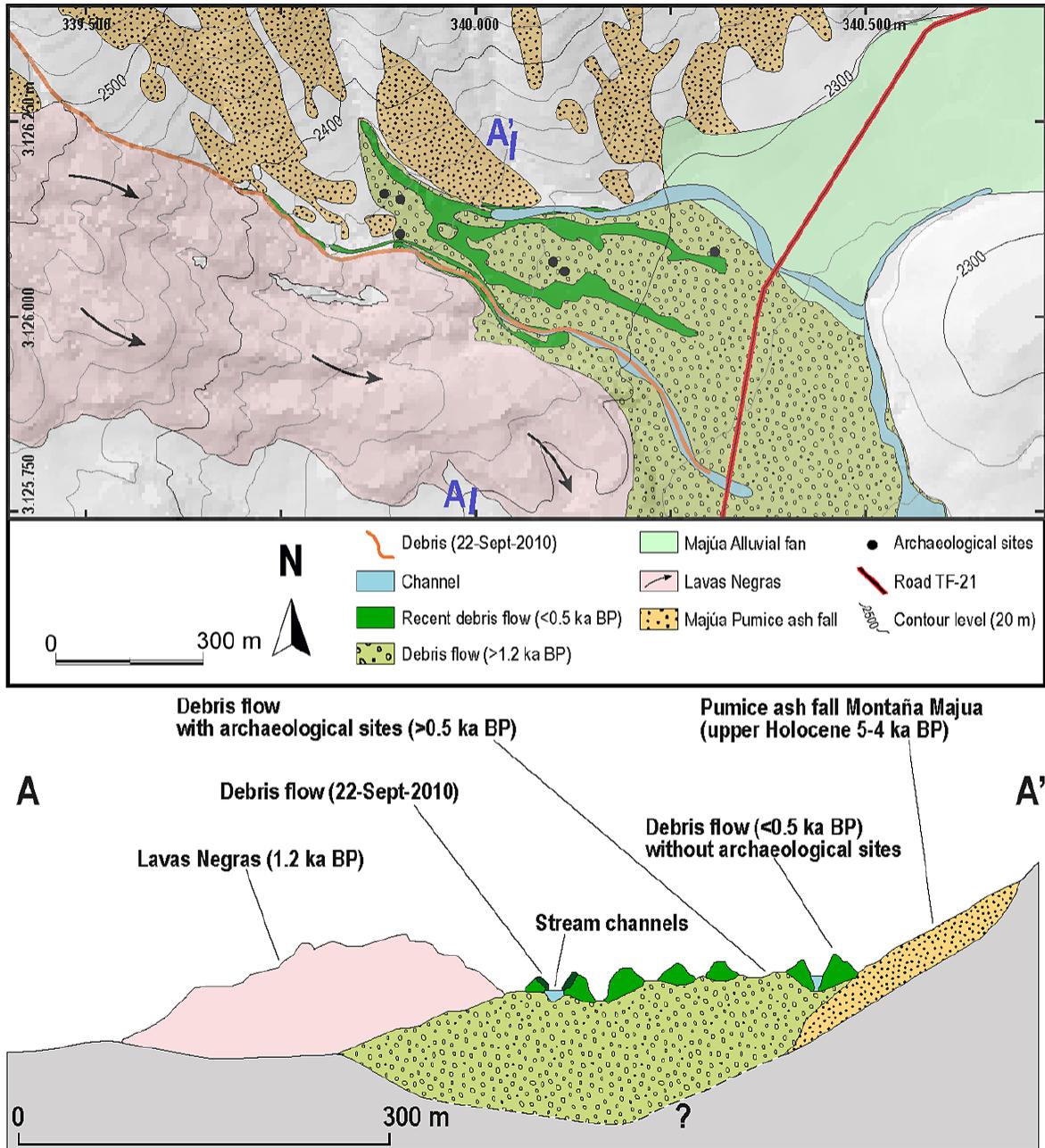


Figure 3. Geomorphological map and cross-section of debris flows at the junction of the *Corredor de La Bola* and *Corredor de La Corbata* ravines and detailed cross section along A-A' (UTM coordinates, WGS84 datum) (after Rodríguez-González et al., 2013).

Figura 3. Mapa geomorfológico y perfil de los debris flows situados en la confluencia de los barrancos del *Corredor de La Bola* y del *Corredor de La Corbata* y corte detallado a lo largo de A-A' (coordenadas UTM, WGS84 datum) (Según Rodríguez-González et al., 2013).

year by the warm dry higher layers blowing from the SW.

The maximal frequency of inversion (97%) appears in the warmest months at the lowest altitude (about 800 m high in July) and the greatest temperature difference is between the base and top of the inversion layer (Dorta, 1996).

The high mountain of Tenerife is especially dry in June, July and August, when Izaña Observatory (2,367 m.a.s.l.) receives a mean of 5 mm·m⁻². In addition, the atmospheric moisture level is very low (below 35%), together with a high number of hours of sun (in June, 27 sunny days and 377 hours of sun), causing a pronounced summer drought (Bustos and Delgado, 2000).

Therefore, the high-mountain climate of Tenerife shows a pronounced seasonality. After data from Izaña Observatory, the winter provides 50.9% of the precipitation (rainfall and snow) and the warm dry summer only 0.7%. Furthermore, the high altitude of Tenerife's summit plateau and ridges together with the rainy season in winter means that some precipitation falls there as snow. The most unstable days are defined by the disappearance of the temperature inversion, replaced by very strong thermal gradients leading to rapid adiabatic cooling of the air (Dorta, 1996), producing heavy rains or snowfalls.

The maximum precipitations in 24 hours at Izaña are over 300 mm·m⁻² a day (360 mm·m⁻² in 1950 and 337 mm·m⁻² in 1993) and the

number of days with snowfall is about 1/3 of the total days with precipitation, although it snows on almost all the days with atmospheric instability in winter.

On the peak of Teide, more than 1,000 m higher than Izaña, we can presume a substantial increase in snowy days. This means that heavy rains able to produce geomorphic processes are infrequent there. Heavy rain events only happen at such high altitude during the warmer months, especially in the early autumn when air masses from tropical or subtropical latitudes arrive in the Canary Islands; but they are very infrequent.

3. Materials and methods

The results were obtained by combining different methods and techniques used in the Geomorphology and Climatic Research fields. After a detailed field survey, obtaining photographs, to compare with others from dates previous to the debris flow event (Figs. 4 and 5), we used a GIS tool to generate contour maps and certain topographical data (slope, length, sample points etc.) (Table 1). A detailed cross-section was also obtained using an optical level (Pentax AP-128) taking measurements on the ground each ½ m (Fig. 6). At four points (located with GPS Garmin Venture HC), we took sediment samples and studied them in the laboratory, separating the fraction finer than 2 mm mesh. This fraction was submitted to a textural analysis by the Bouyoucos method, to get information about the grain-size features, also applying the Munsell Colour scale (Table 2).

Sample	UTM Coordinates	% > 2 mm	% < 2 mm	Munsell Colour
1	28R X: 339016 Y: 3127758	65.15	35.85	2.5YR7/3
2	28R X: 339671 Y: 3126181	31.10	68.90	2.5YR5/3
3	28R X: 339994 Y: 3126057	26.40	73.60	2.5YR5/3
4	28R X: 340160 Y: 3125961	0.00	100.00	2.5YR5/2

Table 2. UTM coordinates, percentage of particles > 2 mm and < 2 mm and Munsell Colour of the 4 samples from the debris flow of 22nd September 2010. 1) Source of sediment in La Corbata. 2) and 3) *Levéés* at the mouth of Corredor de La Corbata ravine, 4) Distal facies of debris flow

Tabla 2. Coordenadas UTM, porcentaje de partículas > 2 mm y < 2 mm y color Munsell de las 4 muestras del debris flow del 22 de septiembre de 2010. 1) Área fuente de los sedimentos, 2) y 3) levées en la desembocadura del barranco del Corredor de La Corbata, 4) facies distal del debris flow.

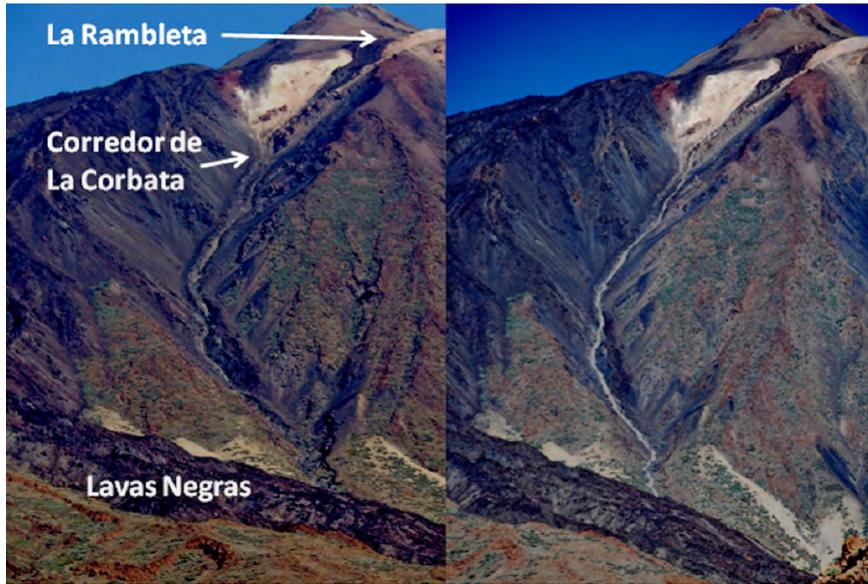


Figure 4. View of *Corredor de La Corbata*. On the left, before 22nd September 2010: on the right, the appearance of channel infill with pale sediments washed down from the fumarole area near the top (~3,500 m).

Figura 4. Vista del *Corredor de La Corbata*. A la izquierda antes del 22 de septiembre de 2010; a la derecha, aspecto del canal relleno con los sedimentos de color claro arrastrados desde el área fumaroliana próxima a la cumbre (~3.500 m).

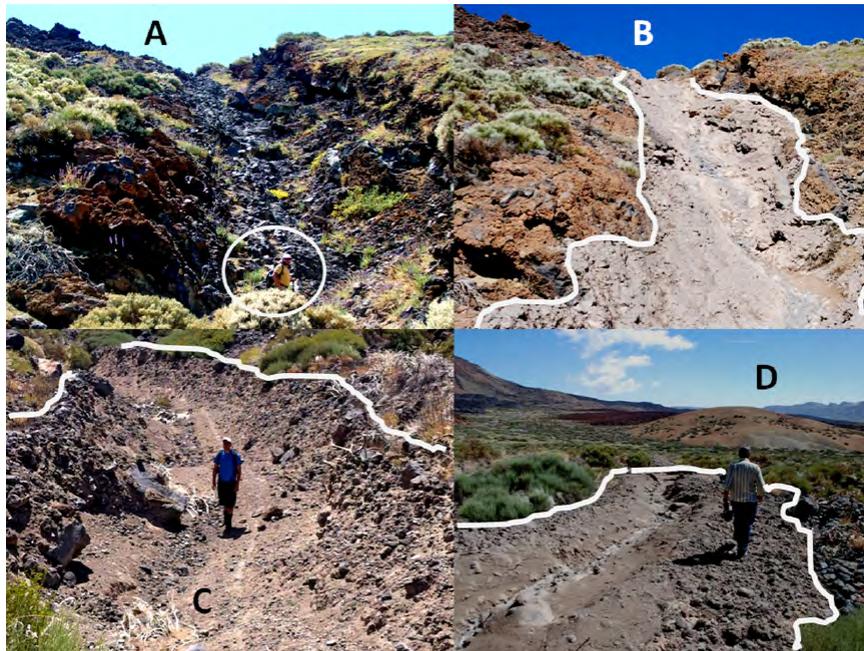


Figure 5. Image of channel eroded by run-off down the ravine after 1.2 ky: A) before 22nd September and B) a few days later. The pale sediments covering the channel are clearly visible (in photo number A the man inside the circle provide the scale). C) and D) view of debris flow infilling the channel in the distal area.

Figura 5. Imagen del canal excavado por el barranco después de 1,2 ka. A) Antes del 22 de septiembre y B) días más tarde. Podemos ver los sedimentos de color claro cubriendo el canal (La figura del hombre dentro del círculo en la foto A proporciona la escala). C) y D) aspecto del debris flow en el área distal.

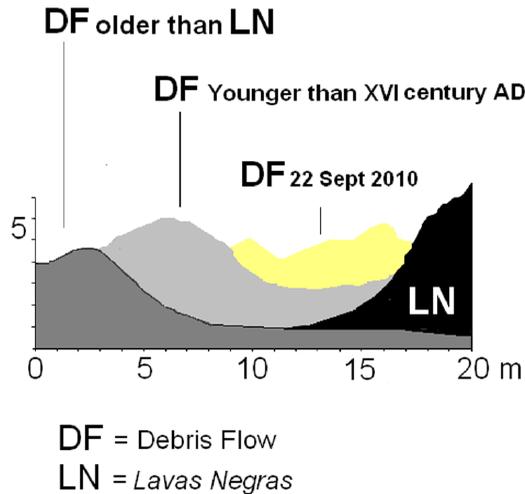


Figure 6. Profile of debris flow formed on 22nd September 2010. Located in 28R X: 339994; Y: 3126057.

Figura 6. Perfil del debris flow formado el 22 de septiembre de 2010. Localizado en 28R X: 339994; Y: 3126057.

The heavy rain that caused the debris flow was studied from two different points of view. Aside from routine climate measurements at the altitude of the island's dorsal ridge, e.g. Izaña Observatory, the first was the study of the precipitation on September 22nd of 2010 in Teide National Park, using data provided by AEMET (*Agencia Estatal de Meteorología*) and another from a pluviograph implemented by IPNA (*Instituto de Productos Naturales y Agrobiología*, CSIC) at a private building in El Portillo. The second was the study of the synoptic situation, including the Meteorological Chart at the 500 hPa level, the atmospheric sounding and the backward trajectories. Finally, using the data file from Izaña Observatory, one of the most important in Spain not only for its location but also the length of climatic series (from 1916 until today).

4. Results

Unusual weather conditions produced intense heavy rain that triggered the debris flow from La Rambleta (~ 3,500 m) down to the base of Teide by Corredor de La Corbata,

halting 20 m from the main road TF-21. The debris flow of La Corbata corridor was clearly visible because of its pale color (Table 2), contrasting with the dark rocks of the surrounding lava flows (Fig. 4).

4.1. Morphometry and sedimentology

The GIS tool provided some morphometric parameters (Table 1): the length (2,505 m), slope in degrees is between 30° to 40°, in the upper and middle part, decreasing to 20° to 10° in the lowest sector (Fig. 2); the surface area of the ravine basin 0.74 km². The coarse estimation of the volume of material moved during this event is around 30,000 m³. More accurate calculation has been impossible because of the difficulties to access to the medium part of La Corbata corridor to take measurement of thickness of debris flow. The debris flow totally infilled the channel excavated by previous erosion after the Lavas Negras eruption (Figs. 5 A and B), overflowing it and producing a typical profile with well-defined levees (Figs. 5 C and D). After the debris flow started, the water probably continued running down the channel, leaving clear signs of erosion by water flow at several points (Figs. 5 C and D).

The sedimentological study, carried out on 4 samples taken in different parts of the debris flow (Tables 2 and 3), shows highly significant textural changes between the sediment source at 3,500 m, the material forming the levees and the most distal facies (Figs. 5 and 6). There was a decrease in the percentage of particles > 2 mm, according to altitude and slope. Inversely, the percentage of the fraction < 2 mm rose 100 % in the distal lobe of the flow. In general, the sediment in the source area presented a sandy texture, while the amount of material < 63 μm increased down the flow (Table 2 and 3). Blocks of rock with angular shapes are also scattered along the debris flow, phonotephrite from the Old Teide outcrops (older than 30 ky) and phonolite from Lavas Negras issued during the last eruption, both with diameters greater than 50 cm.

Sample	% Coarse sand	% Fine sand	% Coarse silt	% Fine silt	% Clay
1	76.27	11.12	2.15	5.41	5.05
2	63.19	15.17	3.72	9.34	8.58
3	52.56	19.87	5.04	12.66	9.87
4	25.23	42.45	6.54	16.44	9.34

Table 3. Texture of the 4 samples of the debris flow of 22nd September 2010. 1) Source of sediment in La Corbata, 2) and 3) *Levéés* at the mouth of Corredor de La Corbata ravine, 4) Distal facies of debris flow.

Tabla 3. Textura de las 4 muestras del debris flow del 22 de septiembre de 2010. 1) Área fuente de los sedimentos, 2) y 3) *levées* en la desembocadura del barranco del Corredor de La Corbata, 4) facies distal del debris flow.

4.2. The storm of 22th September 2010

This rainfall event was produced by a synoptic situation with a *talweg* in the high atmosphere and an invasion of air coming from the South, causing a pronounced tropicalization in the lower layers of the atmosphere, producing rains over the whole Canary archipelago (Fig. 7). The instability was clearly visible in the vertical structure of the atmosphere (Fig. 8). The thermodynamic sounding distinguishes winds coming from the SE and SW, with a clear S component throughout the troposphere. A similar conclusion can be drawn from backward trajectories (Fig. 9). Thus, the temperature was over 0° C up to 4,100 m. a.s.l., which can produce precipitation as rain even on the highest slopes of the volcano.

The maximal rainfall rose to more than 80 mm·m⁻² in sectors of Teide National Park exposed to the SW. In this way the mass of Teide acted as a collecting screen against the moist unstable air coming from the SW.

The precipitation data provides reliable evidence of the magnitude of this rain event in the area of Teide National Park (Table 4). For instance, according to data from the observatory network of AEMET, at Izaña 45.8 mm·m⁻² (three times the average September mean of 15 mm·m⁻²) were collected on the 21st and 22nd. At the Base of Teide, the total 96.0 mm·m⁻² was more than 25% of the annual mean total (355.8 mm·m⁻²).

The data available from the pluviograph installed in the El Portillo area, which provides a cumulative recording of rain each 30 minutes, permits a hyetograph of this storm to be drawn (Fig. 10). Located in a comparatively flat area at some distance from the prominent reliefs, it collected 18 mm·m⁻² between 13.30 and 17.30 h on the 22nd. Of this, 15 mm·m⁻² (83.3%) fell uninterruptedly from 13.30 to 16.00 h, giving an intensity of 6 mm·m⁻²·h⁻¹. Assuming a similar behavior of the rain at the Base del Teide pluviometer (the only one located on the volcano itself), from the total of 96.0 mm·m⁻² 80 mm (83,3%) could have fall between 13.30 – 16.00, resulting in an intensity of 32 mm·m⁻²·h⁻¹.

Pluviometer	Altitude (m)	Precipitation
Base Teide	2,320	96.0
La Angostura	2,341	58.0
Llano Ucanca	2,020	87.3
Encerradero	2,100	118.3
Boca Tauce	2,050	131.0
Tiro Ema	2,071	108.1
Diego Hernández	2,145	50.0
Risco Verde	2,100	54.4
Izaña	2,367	45.8
El Portillo	2,137	84.0
Centro Visitantes	2,100	69.0

Table 4. Precipitation registered in the pluviometers in Teide National Park during the storm on 22nd September 2010. Data from AEMET.

Tabla 4. Precipitaciones en los diferentes pluviómetros del Parque Nacional del Teide producidas por la tormenta de septiembre de 2010. Fuente: AEMET.

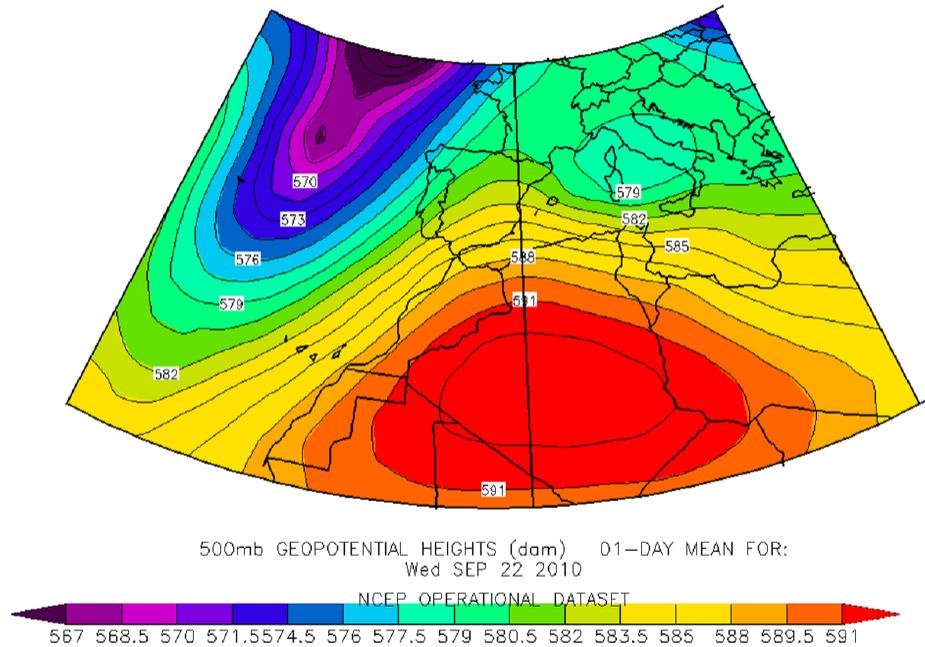


Figure 7. Meteorological chart at 500 hPa on 22nd September 2010 at 12 UTC. Available at <https://www.netweather.tv/forum/topic/46373-understanding-500-hpa-charts/>
 Figura 7. Mapa meteorológico en el nivel de 500 hPa del miércoles 22 de septiembre de 2010 a 12 UTC. Disponible en <https://www.netweather.tv/forum/topic/46373-understanding-500-hpa-charts/>

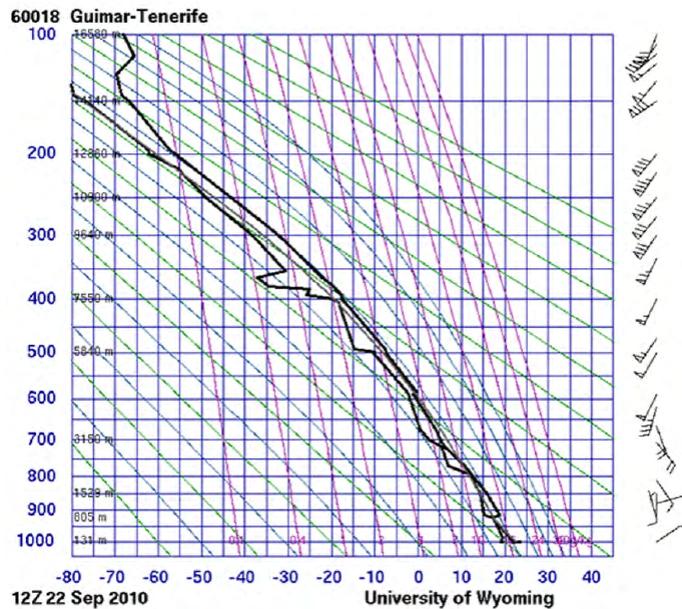


Figure 8. Sounding taken at Guímar meteorological station on 22nd September, 2010. Note the above-zero temperatures at altitudes higher than 3,100 m.a.s.l. Available at <http://weather.uwyo.edu/upperair/sounding.html>
 Figura 8. Sondeo termodinámico de la estación de Guímar del 22 de septiembre de 2010. Podemos ver temperaturas positivas por encima de los 3.100 m.s.n.m. Disponible en <http://weather.uwyo.edu/upperair/sounding.html>

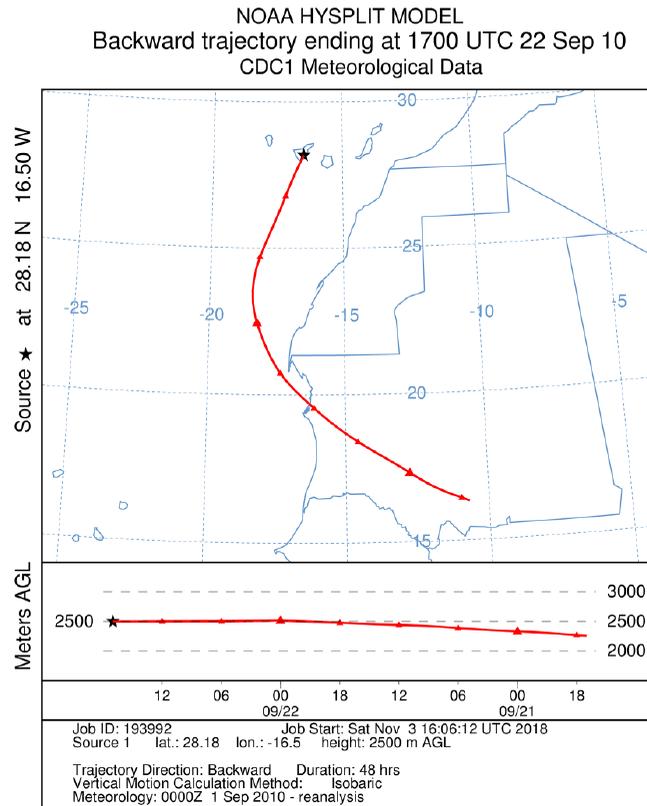


Figure 9. Backward trajectories ending at 1800 UTC on 22nd September 2010.
Available at <http://www.ready.noaa.gov/HYSPLIT.php>

Figura 9. Retrotrayectorias terminando a las 18.00 UTC del 22 de septiembre de 2010.
Disponibile en <http://www.ready.noaa.gov/HYSPLIT.php>

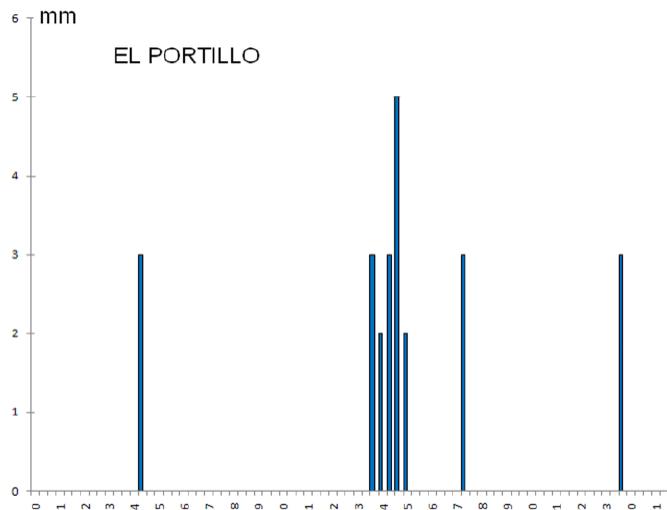


Figure 10. Hyetograph of the storm of 2010. Data taken by a pluviograph installed by IPNA in El Portillo.

Figura 10. Hietograma de la tormenta del 2010. Datos tomados en un pluviógrafo instalado por el IPNA en El Portillo.

5. Discussion

Using the data from Izaña Observatory, it has been possible to detect rain events similar to that of the 22nd September 2010. The statistical analysis of rainfall with totals above 30 mm·day⁻¹ and temperature with minima over 6° C provided an estimate of 15 storms, of which only one was during the spring (May), and summer (August) (Table 5), in the recent years, and the main part in autumn. There is a marked concentration in the 1950s, a period with very abundant rainfall in general for the Canary Archipelago (Hernández-Calvento *et al.*, 1999), moreover a similar situation is perceived in the recent years corresponding to the XXI century (Table 5).

Some of these events (Table 5) show a striking arrival of air from southern latitudes. For instance the situation in September 1951, studied by

Font Tullot (1983), was classified as due to tropical depressions (Font Tullot, 1955 and 1983).

Therefore, the only weather syndromes able to produce runoff down ravines on Teide are 'warm' storms, which happen in early Autumn or Summer, as recently as 2015, but without significant torrential dynamics in the Teide ravines. In that year, from 8th to 14th August, Izaña received 66.2 mm·m⁻² of rain, of which 21.6 mm·m⁻² from 0 to 6 UTC was on the 14th, but without consequences in the debris flow. That rain probably did not fall on Teide volcano itself but in surrounding areas. In this sense it is important to highlight the statistically significant increase, of summer precipitations in the Canary Islands, especially in the high summits (Dorta *et al.*, 2018). These precipitations always fall as rain with an intensity corresponding to stormy events. An example is the atmospheric situation oc-

Date	Minimum temperature	Estimated temperature at 3,500 m (=0.5° C per 100 m)	Maximum wind speed (m·sec ⁻¹)	Dir	Rain (mm·m ²)
22 May 1927	8.4	2.4			32.6
22 Oct 1927	6.6	0.6*			80.6
9 Oct 1937	7.8	1.2*			51.4
30 Sept 1950	6.5	0.5*	17.2	200	31.4
9 Nov 1950	6.4	0.4*	28.1	180	124.0
20 Sept 1951	10.8	4.8	23.1	130	62.7
26 Nov 1952	7.0	1.0*	17.8	200	43.7
8 Oct 1953	6.6	0.6	28.9	290	48.4
30 Sept 1955	8.6	2.6	13.1	130	56.2
12 Sept 1967	8.4	2.4	20.0	230	75.9
13 Sept 1967	6.4	0.4*	22.8	320	58.4
22 Sept 2010	9.6	3.6	24.4	180	44.2
11 Oct 2010	7.5	1.5*	25.3	280	41.0
18 Aug 2005 ⁺	11.3	5.3	21.4	190	29.1
19 Oct 2014	12.2	6.2*	32.2	260	54.4
13 Aug 2015	10.0	4.0	27.7	190	59.2

Table 5. Weather parameters of the 13 storms with heavy rains and temperatures over 0° C, recorded at Izaña (2,351 m a.s.l.). *High probability of snowfall at 3,500 m.a.s.l. *Although this datum did not exceed 30 mm, it approaches the chosen value of 30 mm. The previous day (17th August) another heavy shower fell, registering 20.3 mm.

*Tabla 5. Parámetros meteorológicos de 13 tormentas con lluvias intensas y temperatura por encima de los 0° C registradas en Izaña (2.351 m.s.n.m.). *Alta probabilidad de nevadas a 3.500 m.s.n.m. *A pesar de que el dato no excede de 30 mm, muestra un valor muy próximo a la cantidad elegida de 30 mm y además el día anterior (17 de agosto) cayó otra lluvia de 20,3 mm.*

curred on August 2015 (Table 5). This kind of storms could increase the number of debris flow events like the one showed in this paper.

6. Conclusions

There is no documentary or verbal record of debris flows generated on the southern slopes of Teide volcano for at least the last thirty years, although stormy weather producing heavy rains is normal at Izaña Observatory, where the climate series reaches back to 1916. This usually happens during the coldest season, producing snowfalls above 2,000 m. In this way, the snowfall produces a temporary covering layer, undergoing intense sublimation (related to the very low air-humidity value) and gradual melting. In addition, the water produced by the melted snow percolates into a very porous substrate, formed mainly of rock debris.

However, the substratum is determinant in the triggering of debris flows; the presence of fine material (like sand or silt) is necessary to form the matrix of sediment mixed with water that causes the movement. This condition was fulfilled in the triggering of the debris flow down Corredor de La Corbata, at the top of which there is a clearly visible outcrop of fine pale material produced by fumarole weathering.

This paper forms a basis for future research monitoring carefully the activity of these ravines during the late Summer or early Autumn, when the weather conditions lead to rain at the peak of Teide. This could unleash further debris flows down Corredor de La Corbata ravine and debris falls and slides in other ravines on the southern slope of Teide, a hazardous area regarding the increasing number of cable-car passengers.

The installation of automatic pluviograph devices would be highly advantageous to record rainfall at the top and mouth of Corredor de La Corbata (both places with easy access). Web-cameras would also be very useful to study the effect of rain on the ravine dynamics.

The frequency of summer thunderstorms with heavy rain in the Canary Islands is growing during recent years (Máyer *et al.*, 2017, Dorta *et al.*, 2018). Quite probably, the increased number of 'warm' storms during the summer and early Autumn are due to tropical air arriving in the current context of climate change (Dorta *et al.*, 2018). In this way, Izaña Observatory has recorded an increase of 0.8° C in the average annual temperature during its history (1916-until today), together with a decrease in the number of days with snowfall. In addition, the high-mountain area of the Canary Islands where warming is more evident has undergone a rapid increase in temperature, particularly since the 1970s (Martín *et al.*, 2012). For this reason an increased number of events like that analysed in this paper would be highly probable if the current trends in Global Climatic Change continue.

In addition, this study allows to understand the weather conditions able to produce the genesis of previous debris flows on Teide volcano. The main part of them took place between the 2 ky BP (lava flow from the Montaña Blanca dome) and 1.2 ky BP (the Lavas Negras eruption) (Ablay *et al.*, 1995; Ablay and Martí, 2000; Carracedo, 2006; Carracedo *et al.*, 2003, 2007, 2013; Criado, 2006; Criado *et al.*, 2008; Rodríguez-González *et al.*, 2013). This relative dating coincides with the Roman Warm Period, which probably received more abundant storms from Southern latitudes, involving heavy rains with temperatures over 0° C at altitudes higher than 3,000 m. More recent debris flows, without archaeological remains, could had been produced during historical times (< 0.5 ky BP), pointing to exceptional stormy weather like the hurricane of 1826 (Bethencourt-González and Dorta-Antequera, 2010).

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Online Resources

- <http://weather.uwyo.edu/upperair/sounding.html>
- <https://www.netweather.tv/forum/topic/46373-understanding-500-hpa-charts/>
- <http://www.ready.noaa.gov/HYSPLIT.php>

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