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# Landslides

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# Old and recent landslides of the Barranco de Tirajana basin, Gran Canaria, Spain

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ABSTRACT: The head of the Barranco de Tirajana (BdT), on Gran Canaria island (Spain) is a large natural depression that occupies 35 $km^2$. Its origin and evolution is due to the activity of large landslides which have been occurring since the Quaternary until the present. The bottom of the BdT basin is occupied by a complex group of slide bodies, formally named g.s.d. (gravitational slide deposits) Fm. The boundary between the g.s.d. and bedrock formations, as well as among 28 different landslides, has been established. The movements were mainly translational-type, some of them of extraordinary dimensions. Although most of the slides took place in past ages and are now stable, some of them are still active, like Rosiana landslide, affecting an arterial road and many buildings.

## 1 INTRODUCTION

The Barranco de Tirajana (BdT) is one of the principal ravines of Gran Canaria (Canary Islands, Spain) and it starts in the central-southern part of the island, at about a height of 1600 m, and flows into the ocean on the SE coast (Fig. 1). The BdT has some features in common with other ravines on Gran Canaria and other volcanic islands in the Atlantic (e.g. Gomera, La Palma and Madeira). These are: radial disposal, very deep valleys and a large difference in level from the head to the mouth in a distance of few kilometres.

However, some characteristics of the BdT are specific: (a) it has a large upper basin (an area of 35 $km^2$ and a depth of 900 m) with landslides inside, some of them of extraordinary dimensions (more than 1 km long and 0.5 $km^3$ in volume); (b) its middle channel is narrow and deep, and it crosses a wide range of bedrock formations of the island; (c) its mouth goes through a wide alluvial plain, that prograded into the ocean, and it is actually the main deltaic formation of Gran Canaria; and (d) current climate in the BdT is temperate subtropical, with 375 mm of annual rainfall, and a temperature in winter of 15-20 ºC and in summer of 20-32 ºC.

## 2 THE BARRANCO DE TIRAJANA BASIN

### 2.1 *Origin of the BdT basin*

The upper basin of the BdT is a major form within the volcanic island of Gran Canaria. The hypotheses about its origin have been of three types: (a) a volcanic genesis could explain it as a collapse caldera (Buch 1825, Benítez Padilla 1945); (b) a tectonic genesis was considered as a result of the movement of blocks affecting the whole island (Boucart & Jeremine 1937) or its central part, as a tectonic graben (Hausen 1960); and (c) an erosive genesis has been taken into account because exogenetic processes only seem to have taken place (Fúster et al. 1968, Araña & Carracedo 1980) and, besides, landslides had a main role in the basin evolution (ITGE 1990, Lomoschitz & Corominas 1992).

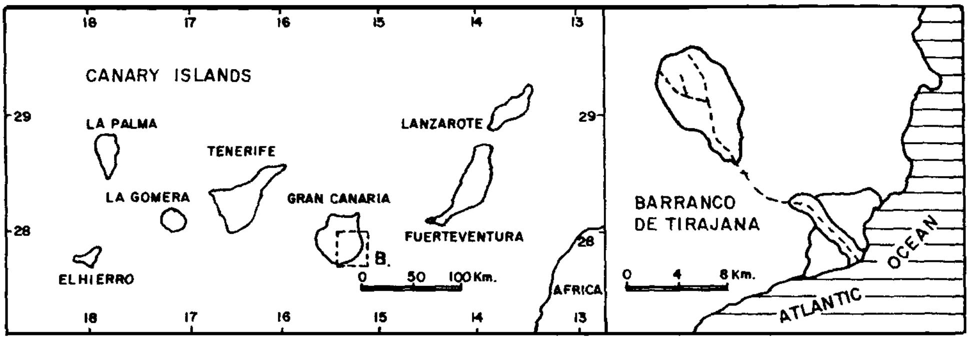


Figure 1. Location of the Barranco de Tirajana (Bdt) on Gran Canaria.

The bedrock formations outcrop in the cliffs and in some points of the basin. The BdT cuts through materials of the three magmatic cycles of Gran Canaria (Table 1).

Table 1. Bedrock geological formations of the BdT. Modified from ITGE (1990, 1992), Pérez-Torrado & Mangas (1993) and Pérez-Torrado et al. (1995).

| Magmatic Cycle | Period | Time (m.y.) | Geological Formations & Rock types |
|---|---|---|---|
| | Pleistocene- | < 0.15 | Basanite lava flows. Pyroclastic cones and maars |
| III | Upper | 0.15-0.3 | Basanite-Nefelinite lava flows. Pyroclastic cones |
| | Pliocene | 0.6-2.7 | Basanite-Nefelinite lava flows. Pyroclastic cones |
| | | 2.9-3.8 | Phonolitic domes |
| II | Lower Pliocene | 3-3.9 | Roque Nublo volcanic breccia |
| . | | 3.9-4.6 | Basaltic, basanitic and tephritic lavas. Pyroclastic cones |
| | | 9.6-13 | Phonolitic Fm. Phonolitic ignimbrite and lavas, interbedded levels of tuff and pumices |
| I | Miocene | 13-14.1 | Trachytic-Rhyolitic Fm. Tuffs, ignimbrites and lavas |
| . | | 14.1-14.5 | Basaltic Fm. Olivine-piroxene basaltic lavas |

Firstly, the erosive hypothesis is based on the lack of evidence to support the other two hypotheses. On the one hand, no signs of tectonic movements appear in the BdT, because bedrock formations are concordant one to each other, and they are not deformed, either by faults or by folds. And, on the other hand, no volcanic edifice or material can be related to the creation of the basin.

After a detailed study, Lomoschitz & Corominas (1996) suggested that only Cycle III basanite-nefelinite lava (Pleistocene - Holocene) erupted during the evolution of the BdT basin, and in no case did they flow into the basin. Besides, the small volume and the deep origin of these lava could not justify either the emptiness or the collapse of a nearly magma chamber.

Consequently, nowadays the erosive genesis hypothesis of the BdT basin is widely accepted. In this way, the term "depression" was proposed by Lomoschitz & Corominas (1997a), rather than "caldera", to name the BdT basin. And once a review had been done about the formation of many erosive calderas around the world, Karatson et al. (1999) put it into the group of "erosive depresssions".

## 2.2 *Characteristics of the landslides*

The bottom of the BdT basin is occupied by a wide and complex group of slide bodies. The authors of the 1:25000 geological map of Gran Canaria (ITGE 1990) drew the general boundary of this sedimentary formation and said that it is formed by gravitational slide deposits (g.l.d.). Besides, they separated the g.s.d. Fm, of erosive origin, from another formation, the Roque Nublo slide facies, that had a volcanic origin, inside Cycle II.

The g.l.d. Fm. includes materials from almost all the geological formations that outcrop around the cliffs of the BdT (see Table 1). At the top, the g.l.d. show thick rocky strata tilted towards the cliffs. From there, and downwards, the texture of the slide bodies appears more and more weathered and weakened, having a chaotic texture in its lower parts. This progressive decomposition of the slide bodies, from the head to the foot, is due to the increasing number of movements that they suffered.

From the geomorphological mapping, scale 1:10,000, and many geological cross-sections 28 landslides had been differentiated in the BdT. Several generations of movement can be recognised, typically consisting of a major primary failure of the bedrock, followed by a succession of smaller, secondary displacements due to sliding from the primary body. Indeed, it has been found convenient to divide the Basin into seven sectors, each containing at least one main primary landslide and several generations of secondary movements (Fig. 2), numbered within a given sector from 1, the oldest, to 4, the most recent.

Each sector has a primary slide body with lengths of 1.2 to 3.5 km (a mean of 2.5 km) and with volumes of 0.18 to 1.35 $km^3$ (a mean of 0.7 $km^3$). Thus, they were extraordinary large movements. In contrast, secondary bodies, which were detached from the primaries, were smaller: 0.3 to 2.3 km long (a mean of 1.05 km) and 4.5 x $10^3$ to 0.45 $km^3$ large (a mean of 0.1 $km^3$).

The 28 large landslides that have been distinguished cover a wide spectrum of slide types. Considering only the main movement of each one, according to Varnes' classification (1978), they are: 12 rock slides, 11 debris slides, 2 debris slump, 2 earth slide and 1 debris flow. Table 2 shows the percentage of each movement type, the areas that were affected and the volumes.

Table 2. Number and percentage of each movement type. Addition and percentage of the surface areas ($km^2$) and material volume ($km^3$) that were affected.

| Movement Type | No | Type (%) | Σ Area ($km^2$) | Area (%) | Σ Volume ($km^3$) | Volume (%) |
|---|---|---|---|---|---|---|
| Rock slide | 12 | 42.85 | 27.55 | 68.65 | 5.37 | 84.17 |
| Debris slide | 11 | 39.28 | 10.35 | 25.8 | 0.89 | 13.95 |
| Debris slump | 2 | 7.15 | 0.55 | 1.37 | 0.03 | 0.48 |
| Earth slide | 2 | 7.15 | 0.48 | 1.19 | 0.01 | 0.15 |
| Debris flow | 1 | 3.57 | 1.2 | 2.99 | 0.08 | 1.25 |

Four main conclusions could be drawn about the types and dimensions of the landslides: (1) all primary landslides were rock slides; (2) the largest volumes of the initial landslides suggest that primary failure was deepseated; (3) the majority of the slides were of rock-slide and debris-slide types, affecting 70 % and 25 % of the total area, respectively; and (4) modes of displacement were predominately translational (rock-, debris-, and earth-slides) consisting of 89 % (4/5) of the total, compared to rotations and flows that compose 11% (1/5).

Failure surfaces were produced within levels dominated by volcanic tephra (tuffs, ashes, ignimbrite and basaltic pyroclasts), rather than lava flows. These materials correspond to the bedrock formations of Cycle I and II (see Table 1). Most reactivations have occurred along the initial planes of failure.

## 3. THE ROSIANA LANDSLIDE

In the context of the BdT basin the Rosiana landslide is the most important historical large landslide (Fig. 3). Persistently active since 1879, its most dramatic movement to date occurred in February 1956, following a period of intense rainfall (272 mm in 24 hours). Within 9 days, some 3 million cubic metres of material destroyed an arterial road and bridge, severely damaged buildings across an area of 0.3 $km^2$ and provoked the evacuation of 250 people (Lomoschitz and Corominas 1997b). Significantly, this destruction resulted from a net downslope motion of only 7 m (Fig. 4). It is a translational slide according to Varnes' classification with a surface-parallel failure plane at a depth between 12 and 25 m. Due to erosion along a ravine, especially during periods of heavy rainfall, the toe of the slide is unbuttressed and so favours continued displacement (Table 3).

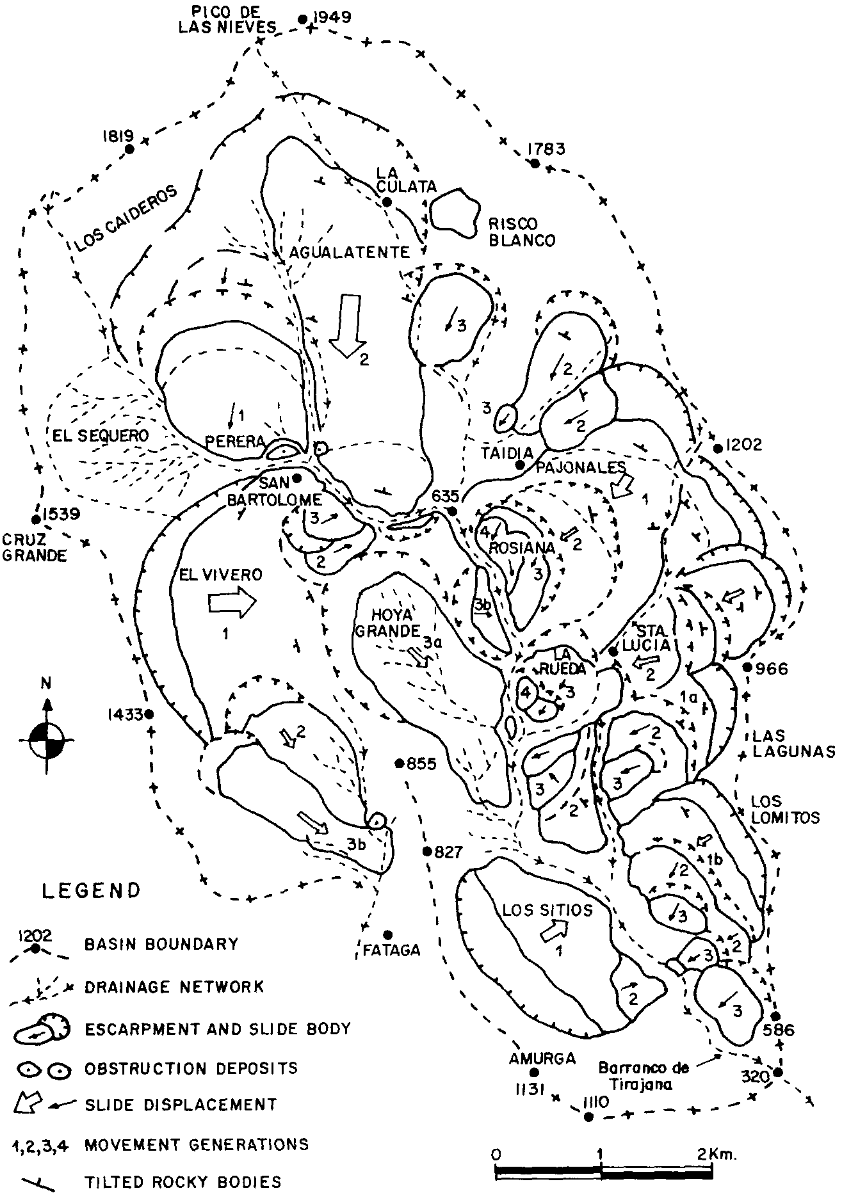


Figure 2. Spatial distribution of the different landslides within the BdT basin. Relative order of movements of each sector (1, 2, 3, 4) has been drawn.

Compositionally, the Rosiana slide consists of broken volcanic material, mostly derived from Miocene and Pliocene trachyte-rhyolite-phonolite formations. Natural cross-sections reveal a chaotic internal structure, composed of heterogeneous, angular fragments (from gravels to boulders) supported by a matrix of clayey-gravel (gravel, sand and clay). Although some sections contain almost exclusively large fragments, most contain some 40% of matrix, a typical particle size distribution being 58% coarse fragments, 20% sand and 22% silt and clay. During the movement the silt-and-clay mixture was cohesionless with a friction angle between 17.7º and 21.6º (Lomoschitz & Corominas 1997b).

Table 3. History of the Rosiana landslide

| Date | Phenomenon |
|---|---|
| 1879 | Rosiana slide activated after large storms. Bed of ravine moved at toe of slide. |
| 1896 | Extension of road Las Palmas-San Bartolomé requires design of bridge across. ravine at toe of Rosiana slide |
| 1921 | Mass movement after heavy rainfall breaks one keystone of bridge, later partially repaired. |
| 1923 | Mass movement after heavy rainfall disables bridge. A replacement girder bridge with reinforced concrete was built 200 m upstream |
| 1956 | Mass movement ($3 \times 10^6$ $m^3$) destroys road and old bridge, 250 people evacuated |
| 1956-Present | New buildings constructed on mobile zone, even though toe continues to creep forward |

Although the toe of the slide has been slowly advancing since 1956, it has become increasingly built upon and today supports over 200 dispersed buildings. Based on periodic measurements of the position of the surviving pillars of the old bridge destroyed in 1956, it appears that the slide has extended by another 0.5 m (i.e. a mean rate exceeding 1 cm per year). The key point is that the slide remains as active in a creeping mode as it was during the decades before the 1956 event.Thus, another rapid movement remains a strong possibility, especially after periods of heavy rainfall.

Principal inferences from the 1956 event are that (1) rainfall appears to have been a triggering factor, and (b) reactivation occurred along pre-existing failure planes. Precipitation in 1956 was clearly exceptional, notably in February, when one third of the monthly average fell in one day. Indeed, the February 1956 movement started on the 16$^{th}$ (544 mm of accumulated rainfall), two days after the maximum rainfall (Fig. 4). Later rainfalls were not excessive, but they were enough to increase the pore fluid pressure and the terrain suffered displacements for 10 days. According to Gumbel's Law, such a rainfall intensity can be expected once every 100 years or so; however, the 1956 event only indicates the importance of rainfall on landslide reactivation, and smaller rainbursts might also be able to trigger damaging increases in the velocity of the Rosiana slide.

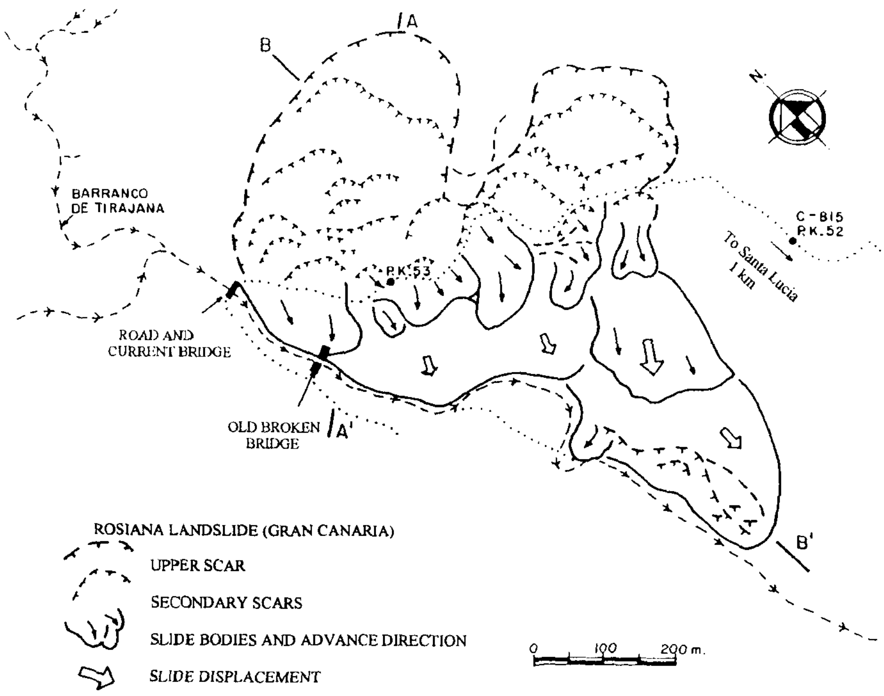


Figure 3. Geomorphological units within the Rosiana landslide.

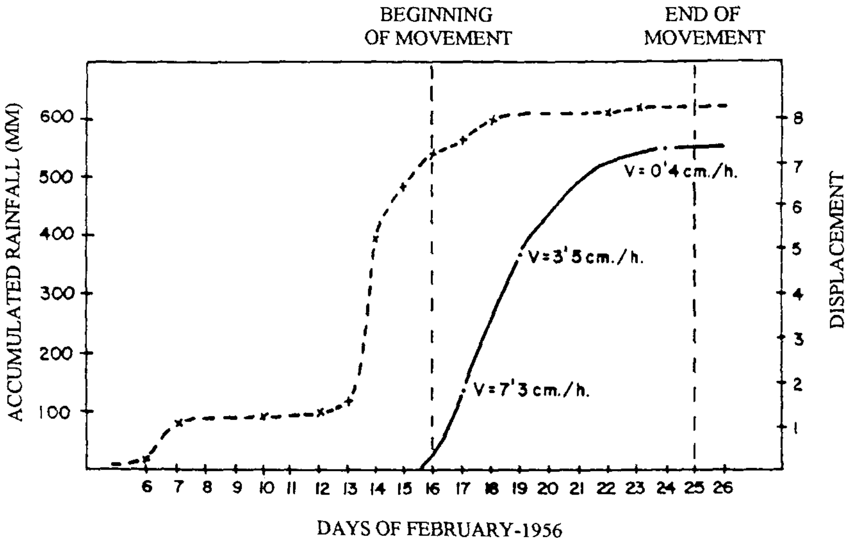


Figure 4. Variation of Rosiana's 1956 movement with cumulative precipitation.

During the period 1951-Present, for which rainfall records are available, rainfall accumulations exceeding 200 mm have been recorded on 12 occasions, each produced over intervals of 4-8 days. Most dramatically, 591.8 mm of rain fell between 2 and 8 December 1991. This is significant since between 1990 and 1996, the support of the broken bridge moved 11.8 cm, compared with a displacement of only 9.3 cm during the preceding 34 years. It is tempting to suggest that most of the 1990-96 movement took place in conjunction with the December 1991 rainfall. If correct, then the 1956 and 1991 data together indicate minimum rainfall conditions of about 400 mm in 4 days for reactivating the Rosiana slide, conditions which occur on a decadal timescale in the BdT.

## 4. SUMMARY AND CONCLUSIONS

The BdT basin was formed by erosive processes and large landslides had a main role in its evolution, since the Pleistocene until the present. Within it there are 28 large landslides. Six of them correspond to primary slide bodies of extraordinary dimensions (a mean length of 2.5 km and a mean volume of 0.7 $km^3$) and they are rock-slide type. The remaining 22 landslides, as secondary bodies, were detached from the primaries and are smaller (a mean length of 1.05 km and a mean volume of 0.1 $km^3$). One of them is still active, the Rosiana landslide. As a whole, the main movements were of rock-slide and debris-slide types, affecting 70% and 25% of the total area, respectively. In addition, modes of displacement were predominantly translational (rock-, debris-, and earth-slides) consisting of 4/5 of the total, compared to rotations and flows that compose 1/5.

The Rosiana landslide is still active and in fact it is the most important large landslide in Gran Canaria. Its most dramatic movement occurred in February 1956, following a period of intense rainfall (272 mm in 24 hours). Within 9 days, some 3 million cubic metres of material destroyed an arterial road and bridge, severely damaged buildings across an area of 0.3 $km^2$ and provoked the evacuation of 250 people. Although Gumbel's Law of rainfall records (1951-Present) show a return period of 100 years for the 1956 event, other historical events (1879, 1921, 1923) and a smaller one (December 1991) have occurred. For the moment, available data indicate minimum rainfall conditions of about 400 mm in 4 days for having reactivated the Rosiana slide.

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