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Landslides determine the geomorphology of the Barranco de Tirajana basin, Gran Canaria

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ABSTRACT

The Barranco de Tirajana (BdT) basin is a 35 km^2 depression located in the central-southern part of Gran Canaria, a volcanic island. The important role of mass movements in shaping the BdT basin has been studied during the last decade. The basin's origin has been under discussion since the last century but its erosive genesis is now widely accepted. Both its origin and morphological evolution were directly related to erosive periods during the Quaternary. These produced backward erosion in the ravine and, as a result, a huge number of landslides occurred in the upper basin. From the Middle Pleistocene to the Holocene, the basin was enlarged and the material from the landslides was transported through a narrow valley and deposited as an extensive alluvial delta fan on the coast.

INTRODUCTION AND GEOLOGICAL CONTEXT

The Barranco de Tirajana (BdT) is one of the main basins on Gran Canaria in the Canary Islands, Spain. It starts in the central-southern part of the island, at a height of 1600 m and reaches the Atlantic ocean on the island's southeastern coast (Figure 1). A distinctive feature of the BdT basin is its morphology; it is a 35 km^2 semi-oval depression, 12 km long and 5 km wide. Its base presents an irregular topography and it is almost enclosed by large rock scarps from 200 m to 350 m high, with zones that reach a difference in height of up to 900 m (Figure 2).

The inner morphology of the basin is formed by a number of large landslides that almost cover the whole bottom. The ravine is 15 km long from basin to coast, where there is a large delta. The delta is directly related to the evolution of the BdT basin because its sediment originated from erosion of the landslide material.

The BdT cuts through a number of the island's bedrock formations that outcrop in the cliffs and in some parts of the ravine bottoms. Three different magmatic cycles were involved in the formation of Gran Canaria. Each cycle is characterised by the presence of specific materials that, in the BdT case, are represented in Table 1.

The bedrock of the BdT has been exposed by erosion and field work revealed Miocene formations (Cycle I) in the south-east part of the depression and outcrops of the younger Cycles II and III in the north-east.

GEOMORPHOLOGICAL MAPPING OF BASIN

Lomoschitz & Corominas [1992, 1996, 1997] studied many of the geological and geomorphological features in the BdT basin. They focussed their effort on: (1) establishing the boundaries between the slide masses and bedrock; (2) separating the slide masses into several slide

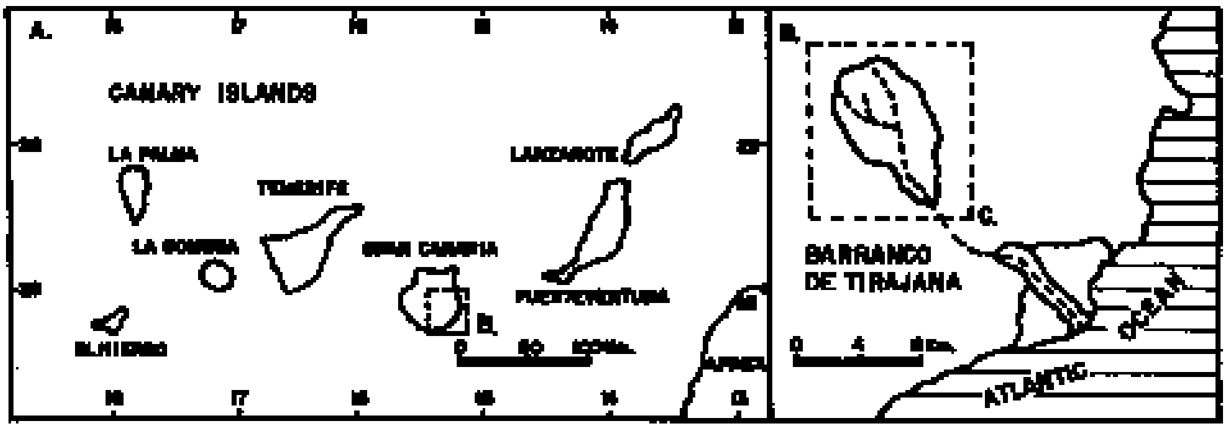

FIGURE 1 Location of the Barranco de Tirajana on Gran Canaria, Canary Islands.

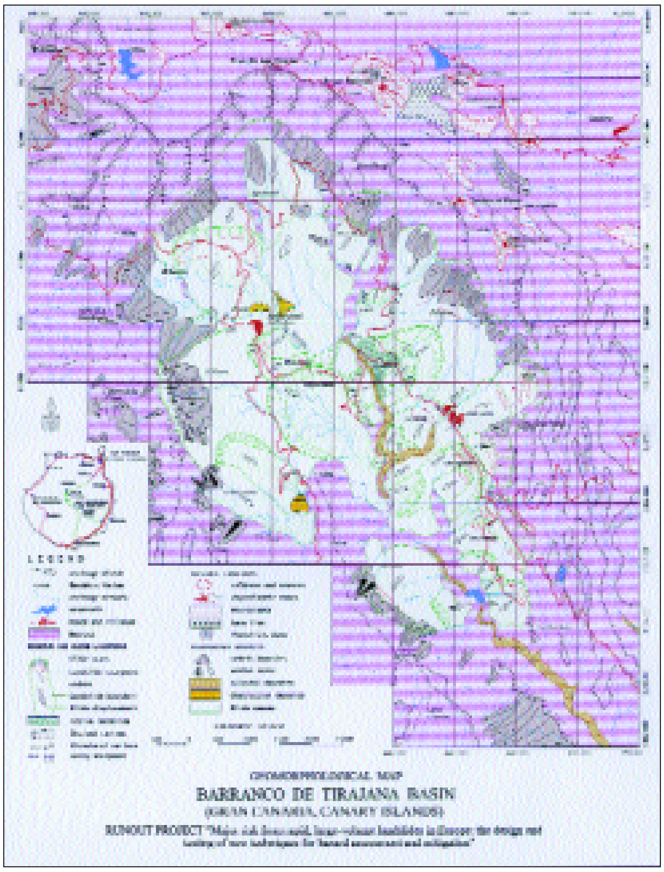

FIGURE 2 Geomorphological map of the Barranco de Tirajana basin.

bodies; (3) a detailed study of each slide; and (4) establishing the relative chronology of the landslides.

We present a geomorphological map of the BdT basin and its surroundings (Figure 2) and offer a new view on the geomorphological features of this area, taking into account the location of the depression on Gran Canaria (Figure 1). We used a scale of 1:25,000 and applied a series of new criteria to the whole area.

GEOMORPHOLOGICAL FEATURES OF THE BEDROCK

The bedrock exposure in the area is mainly recent volcanic landform, *ie*, calderas, craters, pyroclastic cones and deposits, and lava flows. Intense erosion has produced many ravines and rocky escarpments, but left some structural surfaces on the upper areas of the rocky massif as platforms.

SLIDE LANDFORMS

The slide masses are considered as one unit and a demarcation boundary has been drawn to distinguish them from the bedrock. The upper parts of the landslides have scarps behind them, which are sometimes joined together. The landslides have varied forms and sizes, although some specific features have been distinguished in the field and are shown on the map. These include slide scars and escarpments, elongated depressions named 'grabens' in landslide terminology, landslide contours and the slide. The landslides do not follow a regular or simple pattern in the BdT. The Rosiana landslide, in particular, has been indicated as an active slide. Zones with ongoing rock falls are shown as active scree.

SEDIMENTARY DEPOSITS

All the sedimentary deposits in the BdT basin are related to landslides. Firstly, slide masses have all been considered to be one type of sediment, a result of erosion. Secondly, there are a huge number of debris deposits on the upper parts of the slides that come from the upper escarpments formed by the slides. Thirdly, the map shows the main alluvium, which has been produced by intense erosion of recent landslides. In addition, some obstruction deposits have been recognised and located on the map. These were produced when a ravine was closed off by a slide. This slide-obstruction relationship is evident in La Manzanilla landslide.

Our detailed geomorphological survey and map can now be used to prepare a hazard zonation or risk map of the BdT basin, so that areas of potential slides or rock falls can be identified. Our geomorphological map should prove useful to local developers and the authorities.

ORIGIN OF THE BARRANCO DE TIRAJANA BASIN

Three different hypotheses have been proposed to explain the origin of this natural depression. Von Buch

TABLE 1 Bedrock geology of the Barranco de Tirajana (BdT) basin

Magmatic Cycle	*Time*	*Formations and Period (million years)*	*Rock Types*
Cycle III	< 0.15	Recent Basanite Fm. lava flows, pyroclastic cones and maars	
Pleistocene	0.3 - 0.15	Upper Basanite-Nephelinite Fm. lava flows and pyroclastic cones	
Upp. Pliocene	2.9 - 0.6	Lower Basanite-Nephelinite Fm. lava flows and pyroclastic cones	
Cycle II	Roque Nublo	Phonolitic domes Fm.	
Lower	5 - 3.5	Group	Roque Nublo volcanic breccia Fm.
Pliocene		Formations	Basaltic Fm. lava flows and pyroclastic
cones			
Cycle I		Phonolitic Fm. Ignimbrite, lavas and interbedded pumice levels	
Miocene	14.5 - 8.5	Trachytic-Rhyolitic Fm. Tuffs, ignimbrites and lavas	
		Basaltic Fm. Olivine-pyroxene basaltic lavas	

[1825] and Benítez Padilla [1945] proposed a volcanic genesis related to a collapsed caldera. Boucart & Jeremine [1937] and Hausen [1960] proposed a tectonic genesis. Fúster *et al* [1968], Araña & Carracedo [1980], ITGE [1990] and Lomoschitz & Corominas [1992, 1997] proposed an erosive genesis. The latter explained that only exogenetic processes seem to have taken place during the evolution of the BdT and that landslides had played the main role.

The hypothesis of a collapsed caldera was rejected because no volcanic edifice or material can be related to the creation of the basin. Neither is there any sign of tectonic movement in the BdT, since bedrock formations are concordant and there are no faults or folds in the area. The erosion hypothesis for the basin's genesis is today widely accepted. Lomoschitz & Corominas [1997] proposed the term 'depression' for the BdT basin, and 'caldera' has been rejected.

CHARACTERISTICS OF THE LANDSLIDES

Several types of mass movements have been distinguished within the BdT basin, falling into two main groups: slides and rock falls.

LANDSLIDES

The landslide areas have six characteristics (Figure 3): (1) 28 different slides have been distinguished and each one suffered several general or partial movements; (2) they do not follow fixed schemes, either in their lithology and structure, or in their external morphology; (3) the landslide dimensions are very variable but all of them are included in the large landslide category according to the UNESCO classification [UNESCO, 1976] (see Table 1); (4) the fabric of the slide bodies appears more and more weathered and weakened downslope due to the increasing number of movements suffered, resulting in a chaotic arrangement in the lower parts; (5) all the landslides have moved in the direction of the BdT; and (6) even though the largest landslides may have advanced in a direction perpendicular to the drainage network, the smallest ones have frequently moved at an oblique angle to it.

Two groups of slide bodies have been distinguished according to their dimensions and their relative time of activity. The main landslides are deep (deposits 120 m to 300 m thick) and large (1 km to 3.5 km long); the secondary bodies, which arose from the main slides, are smaller (0.4 to 2.3 km long) (see Table 2).

In general terms, the slide surfaces that were initially produced by the primary movements were also used by secondary movements. Failure surfaces cut materials that belong to the Thrachytic-Rhyolitic Fm, the Phonolitic Fm and the Basaltic Fm belonging to Cycle II (see Table 1). These are specifically volcanic tuffs and ashes, beds of ignimbrite and layers of basaltic pyroclasts. Surfaces between rock strata also formed sliding surfaces and occasionally included sedimentary deposits between the volcanic lavas.

The 28 large landslides distinguished here cover a wide range of slide types. Considering only the main movement of each one, according to Varnes' classification [Varnes, 1978], there are: 12 rock slides, 11 debris slides, 2 debris slumps, 2 earth slides and 1 debris flow. Table 3 shows the percentage of each movement type, the areas affected, and the slide volumes.

ROCK FALLS

The heads of the primary landslides are covered by large scree deposits with an average length of 500 m, occasionally up to 800 m (Figure 2). In general terms, the movements that caused these deposits were rock falls.

The upper volcanic materials that appear in the bordering scars of the depression show a gentle dip to the south-east of the island. These materials (essentially phonolite, volcanic breccia and basanite have vertical joints that produce slightly separated rock columns. Once

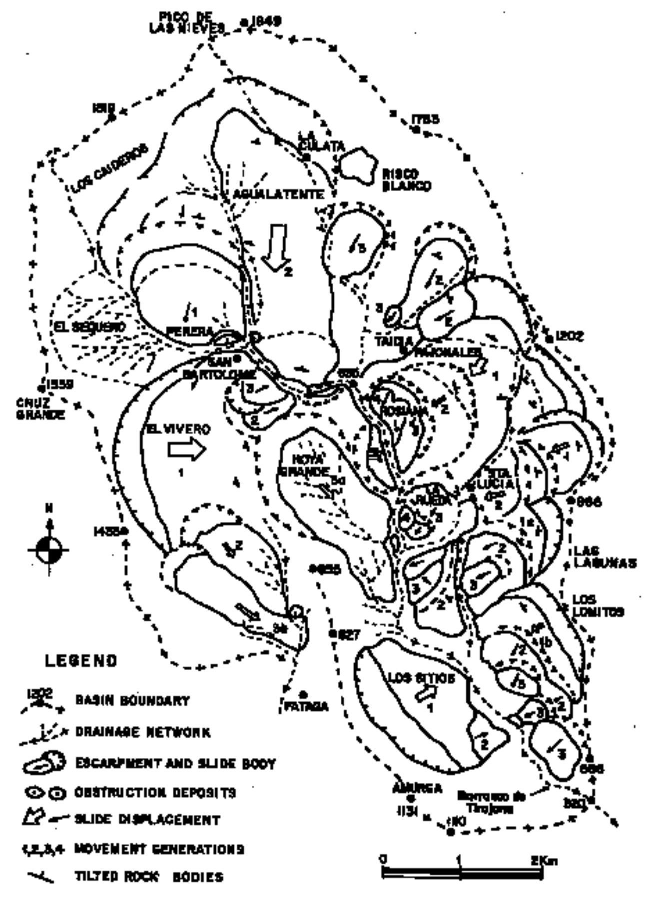

FIGURE 3 Map of the different landslides within the Barranco de Tirajana basin. Relative order of movements (I, II, III, IV) of each sector has been drawn.

TABLE 2 Landslide characteristics and dimensions

Quantitative features	*Main bodies*	*Secondary bodies*
Affected surfaces (km^2)	1.5-6.5 (3.03)*	0.15-2.5
Longitudinal length (km)	1-3.5 (2.03)*	0.4-2.3
Deposit thickness (m)	120-300 (185)*	20-200
Deposit volume (km^3 or m^3)	0.8-1.35 km^3 (0.63)*	0.5x106 m^3 - 0.3 km^3

*average values given in brackets

TABLE 3 Numbers, surface areas (km^2) and volumes (km^3) of different landslide types and as percentages of total landslides

Movement type	*No. of occurrences*	*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

primary slides had occurred, the rocks were freed of lateral pressure and the columns became progressively detached from the bedrock by topple movements. Then, the rock columns crashed on to the slopes, were broken into several parts, and descended bounding and rolling down slope, resulting in debris deposits of scree.

Only a small number of these screes now belong to currently active rock fall zones (Figure 2). Today, the higher risk related to rock falls is concentrated on a few zones where roads are affected. Nowadays falls generally involve small blocks (0.5 m to 4 m large) and isolated rock avalanches occur on only a few occasions; both processes are related to periods of heavy rainfall.

EVOLUTION OF THE BARRANCO DE TIRAJANA BASIN

MAIN STAGES

To establish the chronology of the different events that took place in the development of the depression, we took into account: (a) forms that have been modified by younger processes; (b) morphology of the drainage network; (c) relative antiquity of the forms; (d) degree of weathering of the slide material; and (e) present location of the slide bodies. As a result, we established four stages of landslides (Figure 4).

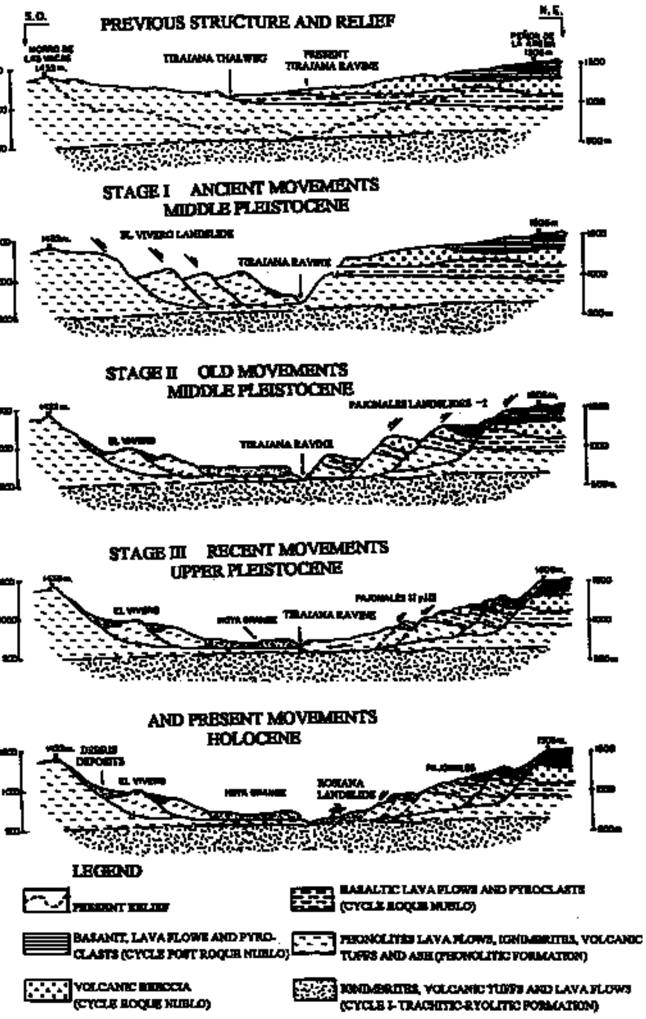

FIGURE 4 Idealised SW-NE cross-section showing the evolution of the Barranco de Tirajana basin during the Quaternary.

Stage I (ancient movements) includes the landslides whose failure surfaces have remained as a relict on the present river bed of the ravine and they reveal the bedrock. In general, these landslides have large grabens (in landslide terminology) at their heads that are extensive depressions filled with sediments. The slide rock masses appear very weathered and thus have a much clay and silt in the matrix.

The slides of Stage II (old movements) have failure surfaces that coincide with the present level of the ravine. They are better conserved than Stage I and show well developed scars and depressions partially covered by scree deposits.

Recent movements correspond to Stage III of the evolution of the BdT. These landslides have well preserved morphologies. They are inter-related with the development of the present drainage network, since the landslides' feet invade the bottom of the ravine. Moreover, the important contribution of the bed load has provoked the formation of braided channels.

Slide masses that have slid again later on belong to stage IV.

AGE OF THE DEPRESSION

Most of the bedrock formations shown in Table 1 are found in the slide masses, even the basanite nephelinite flows of Cycle III. The age of these basanite nephelinite flows is between 2.9 and 0.6 million years [ITGE, 1992]. The oldest age limit for the depression has therefore been established at 0.6 million years and the ancient slide movements (Stage I) must be younger. Nevertheless, new samples of this formation have been taken in order to obtain a more accurate date for the materials involved in the oldest movements.

In addition, we are now studying in detail a sedimentary deposit resulting from an obstruction of the ravine in Stage II. This deposit is about 20 m thick and includes a number of sequences of fine sands, silt and gravels that filled a closed depression. El Vivero landslide formed this depression when it crashed into Agualatente landslide (see Figure 2). Its toe was eroded several times and new activations of the landslide were triggered. The sediments accumulated in periods when the ravine was closed.

Small pieces of charcoal have been found in the central part of these deposits and these have been dated by C-14 techniques giving a minimum upper age of 51,700 BP. Other OSL (optically stimulated luminiscence) analyses are still in progress. As a result, the landslides of Stages I and II have to lie in the interval 600,000 years to 51,700 BP (Middle to Upper Pleistocene), but we need more information to fix the beginning of the movements. A thick pyroclastic layer covered by a scree deposit over the El Vivero landslide has recently been investigated for this purpose. It is being dated at the moment and will give us a new upper limit to the age for the depression.

CAUSES OF THE LANDSLIDES

There are two possible causes to explain the triggering of the landslides: (a) heavy or persistent rainfall periods occurred in a quite different climate to today's; and (b) seismic activity related to volcanic events. The current climate in the BdT is temperate to subtropical with isolated periods of rainfall (annual mean of 375mm) and temperatures between 15 °C and 32 °C throughout the year. These weather conditions could not justify the intense erosion and the large landslides that have taken place in the BdT basin. However, if we consider the climatic variations during the Quaternary in the Sahara and the northwestern Canary Islands, we find attractive possibilities. During the Pleistocene and Holocene, there were three main wet periods. The first one corresponds to the interval 125,000 to 90,000 [Petit-Maire, 1992]; the second occurred between 42,000 and 23,000, and the third about 9,500 years ago [Meco *et al*, 1997].

All of these periods correspond to Stage III, so these landslides were probably triggered by humid conditions during the Quaternary. Besides, current movements are directly related to heavy rainfall. Nevertheless, the triggering of movements in Stages I and II could also be related to seismic activity, since there were many volcanic events on the island during the Lower and Middle Pleistocene. No climatic data for these periods are available at the moment.

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RÉSUMÉ

Le bassin de Barranco de Tirajana (BdT) est une dépression de 35 km^2 situé dans la partie centrale sud de Grande Canarie, une île volcanique. Le rôle important de mouvements de masse donnant forme au bassin de BdT a été étudié durant la dernière décennie. L'origine du bassin a été en discussion depuis le siècle dernier mais sa genèse érosive est maintenant largement acceptée. A la fois son origine et son évolution morphologique ont été directement liées à des périodes d'érosion durant le quaternaire. Ceux-ci ont produit une érosion rétrograde dans le ravin et le résultat est qu'un grand nombre de glissements de terrain se sont produits dans le bassin supérieur. Depuis le pléistocène jusqu'à l'holocène, le bassin a été agrandi et le matériel des glissements de terrain a été transporté à travers une vallée et déposé sur la côte comme un delta alluvial extensif en forme d'éventail.

RESUMEN

La cuenca del Barranco de Tirajana (BdT) es una depresión de 35 km^2 localizada en la parte central meridional de Gran Canaria, una isla volcánica. Durante la pasada década se estudió el importante papel de los movimientos de tierras en el moldeado de la cuenca BdT. El origen de la cuenca es tema de debate desde el siglo pasado, pero actualmente se acepta de modo general su génesis erosiva. Tanto su origen como su evolución morfológica estuvieron directamente relacionados con períodos erosivos del Cuaternario. Estos produjeron una erosión hacia atrás en el barranco y, como resultado se produjeron una enorme cantidad de corrimientos de tierra en la cuenca superior. Desde el Pleistoceno medio hasta el Holoceno, la cuenca ha aumentado y el material de los corrimientos de tierras fue transportado a través de un valle estrecho y depositado en forma de un ancho abanico de delta aluvial en la costa.