Catastrophic collapse of the volcanic island of Hierro 15 ka ago and the history of landslides in the Canary Islands

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ABSTRACT

Landslides play an important role in the evolution of many volcanic islands, producing huge fields of blocky volcanic debris on their submarine slopes. Sidescan sonar images presented in this paper provide evidence for a large debris avalanche, El Golfo, on the northern flank of Hierro Island in the Canary Islands. Angular blocks, as much as 1.2 km across and 200 m high, cover the debris avalanche surface. El Golfo avalanche is related to both the Canary debris flow and a volcaniclastic turbidite found in the Madeira abyssal plain 600 km west of the Canaries. Dating of the turbidite and the failure scarp onshore indicates that the failure probably occurred between 13 and 17 ka. There appears to be a general correlation between volcaniclastic turbidites in the abyssal-plain sequence and landslides in the Canaries during the past 750 ka. Tentatively, this correlation suggests that seven major landslides have affected the Canaries in that time.

INTRODUCTION

Catastrophic landsliding is now widely recognized as an important process in the evolution of many volcanic islands (Lipman et al., 1988; Moore et al., 1989, 1994; Cochonat et al., 1990; Holcomb and Searle, 1991; Watts and Masson, 1996). Individual slumps and debris avalanches on the flanks of the Hawaiian Islands, for example, can incorporate up to 5000 km³ of material (Moore et al., 1989). In the Canary Islands, the precise role of landsliding in island evolution has provoked much controversy. Deep coastal embayments and straight-sided valleys with arcuate headwalls have been cited as evidence for both landsliding and caldera collapse (Ridley, 1971; Ancochea et al., 1990; Holcomb and Searle, 1991; Carracedo, 1994; Marti et al., 1994; Watts and Masson, 1996). An additional alternative hypothesis based on multiple cycles of erosion and filling of valleys by lava flows has also been proposed (Palacios, 1994). However, recent detailed mapping of areas of the submarine flanks of the Canaries has revealed much new evidence of landslide deposits, strengthening the case for large-scale slope failure as a principal agent of island destruction (Holcomb and Searle, 1991; Watts and Masson, 1996; this paper).

This paper presents new evidence for a major debris avalanche, El Golfo, on the northern flank of Hierro Island (Fig. 1). The avalanche is related to both the El Golfo embayment on the island and the Canary debris flow on the island slopes. A more general examination of the relation between Canaries landslides and volcaniclastic turbidites in the Madeira abyssal plain to the west of the Canaries suggests that the abyssal-plain turbidite sequence records the history of island landslides.

EL GOLFO DEBRIS AVALANCHE

The Canary debris flow originated as a large superficial sediment failure at about 4000 m water depth on the western slopes of the islands of Hierro and La Palma (Fig. 1; Masson et al., 1992). New high-resolution sidescan sonar and profile data covering part of the debris flow head and the area immediately upslope, obtained with the towed ocean bottom instrument (TOBI) deep-tow system (Murton et al., 1992), show that the debris flow merges upslope, at between 3500 and 4000 m water depth, with a blocky debris avalanche deposit, similar to those described from other oceanic islands (Figs. 2 and 3; Lipman et al., 1988; Moore et al., 1989; Cochonat et al., 1990; Holcomb and Searle, 1991).

The sidescan sonar data show that the debris avalanche surface is covered by angular blocks up to 1.2 km across (Fig. 2). TOBI 7 kHz profiles show blocks rising up to 200 m above the adjacent sea floor. Some blocks are irregular in shape; others are tabular and show evidence of original bedding (Fig. 4). The largest blocks show some concentration toward the avalanche center; both block size and abundance decrease toward its margins (Figs. 2 and 3). Sidescan coverage in the narrower upslope part of the avalanche, although limited, suggests an absence of large blocks, at least on the avalanche surface, in this area.

Relation to El Golfo Embayment, Canary Debris Flow, and b Turbidite

The obvious spatial relation between the offshore debris avalanche, as mapped from GLORIA and TOBI sidescan sonar data, and El Golfo embayment on Hierro indicates that the 900 m onshore scarp that heads El Golfo depression is the avalanche headwall (Fig. 3). Offshore, a 400-m-high northeast-facing escarpment some 8 km from the northwestern tip of Hierro, seen on a single profile crossing, suggests that the headwall escarpment continues at least that far offshore (Fig. 3).

The relation between El Golfo debris avalanche and the Canary debris flow is more difficult to ascertain. On the two west-northwest–east-southeast TOBI transects that cross from one debris facies to the other

Figure 1. Location of debris flows and debris avalanches around western Canary Islands. Probable landslide sites on islands: 1—El Golfo, 2—Julan, 3—Las Playas, 4—Taburiente-Cumbre Nueva, 5—Orotava, 6—Icod, 7—Guimar. Note that Julan debris avalanche is not related to Saharan debris flow, but is much older and was truncated by that debris flow. Bathymetry is in kilometres.
(Fig. 3), the sidescan data show no distinct boundary. In Figure 3, the boundary has been drawn as an envelope around the field of avalanche blocks; this envelope coincides with a step in the sea-floor bathymetry, defining a relatively steep debris avalanche nose 50–75 m high, on both TOBI profiles crossing the boundary. Along the northern edge of the debris flow, TOBI sidescan and profile data show a series of extensional faults, together interpreted as a complex debris-flow headwall zone (Fig. 3). These faults continue upslope into the debris avalanche, suggesting that the flow postdates the avalanche. However, extensional faults are largely absent from the TOBI transect up the center of the debris flow, giving the impression that, in this area, the headwall zone is buried beneath the avalanche, which therefore appears younger. The best explanation is that both avalanche and debris flow occurred simultaneously, minor local differences in the timing and style of failure giving rise to the observed local superposition of debris facies. On the basis of geotechnical calculations, loading of the slope sediments by the El Golfo debris avalanche is likely to have triggered the Canary debris flow (J. Roberts, 1994, personal commun.).

The Canary debris flow was deposited simultaneously with a volcanioclastic turbidite (b in the sequence of Weaver and Kuijpers, 1983) on the Madeira abyssal plain (Weaver et al., 1994); both originated from the same area of the island slopes (Masson, 1994). Thus, the b turbidite, Canary debris flow, and El Golfo debris avalanche must be closely related and are probably parts of one slope failure deposit. Even so, the precise (three-way) relationship among them is still not fully understood. In particular, it is not certain whether there is a direct relationship between debris avalanche and turbidite (as off Hawaii; Garcia and Hull, 1994) or whether the turbidite is a more distant relative of the avalanche, spawned by the debris flow. However, the turbidity current and debris flow followed significantly different flow paths across the continental rise (Fig. 1; Masson, 1994), suggesting that the turbidity current was directly derived from the debris avalanche farther upslope and that an intermediate debris flow is not required for turbidite generation. This relation must be established if the abyssal-plain volcanioclastic turbidite sequence is to be used as a record of volcano flank landslides, because it is clear that not all landslides generate debris flows in the island slope sediments (e.g., around Hawaii; Moore et al., 1989).

**Age of the El Golfo Debris Avalanche**

The age of the El Golfo debris avalanche can be estimated from its correlation with the Canary debris flow and b turbidite. The turbidite was emplaced “some time during the last deglaciation” (Weaver and Rothwell, 1987), at the boundary between oxygen isotope stages 1 and 2, indicating an age in the (maximum) range of 9–15 ka in terms of 14C dating (e.g., Fairbanks, 1989). This corresponds to a “true” age between 10 and 17 ka, calibrated relative to U-Th dates (e.g., Bard et al., 1990). Published K/Ar dates from pre- and postlandslide volcanic events on Hierro provide alternative age constraints, indicating that the landslide took place before 17 ± 5 ka and probably after 35 ± 4 ka (Guillou et al., 1995). More recent work (H. Guillou, 1995, personal commun.) has refined the younger date to 15 ± 2 ka. The two sets of dates, from turbidite and volcanic sequences, are clearly compatible within their error margins, and together indicate a likely landslide age of between 13 and 17 ka.
Volume of Slope-Failure Deposits

The El Golfo debris avalanche affected an area of 1500 km², of which about one-third is slide scar and two-thirds is avalanche deposit. The volume of the avalanche deposit is impossible to estimate directly, because information about its thickness is lacking. However, a crude estimate of the volume of the slide scar, based on its area and the height of its marginal scarps, gives 250–350 km³. This is about one-fifth the volume of the Alikalandslide of Hawaii, believed to have caused the enormous tsunami that reached a height of 325 m on the neighboring island of Lanai (Moore and Moore, 1984). Nevertheless, the El Golfo landslide could have had huge tsunami-generating potential, and tsunamis only a few metres high can cause damage, even after crossing entire oceans (Shepard, 1977). In total, the debris avalanche, Canary debris flow (Masson et al., 1992), and b turbidite (Weaver and Rothwell, 1987) incorporated 700–800 km³ of rock and sediment.

HISTORY OF LARGE LANDSLIDES IN THE CANARY ISLANDS

Evidence for Landslides

The relation between El Golfo embayment on Hierro and large-scale landsliding suggests that similar structures on other Canary islands have a similar origin. On the basis of their morphology, Hierro, La Palma, and Tenerife would appear to be the islands most clearly affected by landsliding. Probable landslide scars include the El Golfo, Julian, and Las Playas embayments on Hierro (Holcomb and Searle, 1991; Carracedo, 1994; this paper), the Taburiente-Cumbre Nueva “caldera” complex on La Palma (Carracedo, 1994), and the Orotava, Icod, and Guimar Valleys on Tenerife (e.g., Ancochea et al., 1990) (Fig. 1). Debris deposits found off the north coast of Tenerife, related to the Orotava and Icod Valleys onshore (Watts and Masson, 1996), clearly show that landsliding has played an important role in the evolution of Canadas caldera, which dominates the central part of Tenerife.

Onshore Evidence for the Age of Landslides

On land, few landslides have been dated. Exceptions are the El Golfo embayment on Hierro, dated between 15 and 35 ka (discussed above), and the Orotava and Icod Valleys on Tenerife. On the basis of K/Ar dating of pre- and postfailure volcanic and pyroclastic flows, Ancochea et al. (1990) suggested that the Orotava Valley formed between 800 and 560 ka and the Icod Valley formed about 170 ka. More recent work by Marti et al. (1994) confirms the age of Icod, but casts some doubt on the exact age of Orotava, which K/Ar dates (considered reliable by these authors) appear to constrain to between 650 and 370 ka. The age of Icod is also supported by the thickness of post-failure sediment covering the failure deposit offshore (Watts and Masson, 1996).

Correlation of Landslides and Abyssal-Plain Turbidites—A Remote Measure of the Frequency of Landslides?

The correlation of the b turbidite and El Golfo debris avalanche (and Canary debris flow) suggests that the volcaniclastic turbidite sequence in the Madeira abyssal plain might record the history of large landslides in the Canaries. To test this hypothesis, all available evidence concerning the age and source of Madeira abyssal-plain volcaniclastic turbidites and the ages of landslides on the islands has been compiled (Fig. 5). Seven volcaniclastic turbidites, ranging in volume from <5 to 125 km³, have been deposited in the abyssal plain during the past...
Oxygen Isotope Stage 3

Volcaniclastic Turbidites

Island Flank Collapses

0

100

200

300

400

500

600

700

A.C.E. (ka)

Hierro (El Golfo)

North Tenerife (Icod)

North Tenerife (Jalal)

North Tenerife (Izalco)

Hierro (Julan)

Hierro (Orotava)

Figure 5. Comparison between ages of volcaniclastic turbidites in Madeira abyssal plain sequence (letters) and dated landslides in Canary Islands, strongly suggesting correlation between the two phenomena. Turbidites are dated with reference to oxygen isotope record (Weaver et al., 1992). Squares mark turbidites with geochemical signature indicating derivation from western islands of Hierro and La Palma (Pearce and Jarvis, 1996); circles indicate derivation from islands farther east; geochemical studies have not been undertaken on remaining volcaniclastic turbidites.

CONCLUSIONS

A major debris avalanche, recognized on sidescan sonar data from the slopes of the Canary Island of Hierro, created the El Golfo embayment on the island and gave rise to the Canary debris flow and a major turbidite that reached the Madeira abyssal plain, 600 km west of the Canaries. Dating of the turbidite and of pre- and postavalanche lavas onshore indicates that the landslide probably occurred between 13 and 17 ka. A general link can be inferred between landslides in the Canaries and volcaniclastic turbidites deposited in the Madeira abyssal plain. If this correlation is correct, seven major landslides have affected the Canaries in the past 750 ka (Fig. 5).

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