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New sonar evidence for recent catastrophic collapses of the north flank of Tenerife, Canary Islands

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Abstract Previous sonar surveys show that the north flank of Tenerife has been subject to at least four major landslides during the past 1 Ma. The youngest, Icod, affected the region to the north of the Teide–Pico Viejo complex, the world's third highest oceanic volcano. Recently, we obtained the first detailed acoustic images of Icod using a deep-tow side-scan sonar. The images suggest that Tenerife's north flank has experienced at least two types of flow deposit in the recent past. The older flow deposit, Icod I, is characterised by a 15- to 20-km-wide, >65-km-long, chaotic debris avalanche deposit which includes several very large blocks. We believe the deposit to be ~170 ka, and that it represents the mass-wasting products of the Cañadas edifice, remnants of which are now found in the Las Cañadas caldera wall. The younger flow deposit, Icod II, associated with a shute in its proximal part, appears to have produced a less chaotic deposit in its distal part which clearly preserves flow structures such as latitudinal boulder ridges and longitudinal shear structures. The sonar images cannot determine how much younger Icod II is than Icod I, although it is likely that they are a consequence of the same lateral collapse event. There is evidence from the shute area for erosional scour and sediment deposition since the Icod landslide. If this is correct, then it suggests that mass wasting is an ongoing process that has already started to modify the Teide–Pico Viejo complex itself.

Keywords Volcanoes · Landslides · Debris avalanches · Calderas · Canary Islands

Introduction

There is accumulating evidence that large-scale lateral collapses play a major role in the evolution of terrestrial volcanoes. On the continents, recent magmatic blasts (e.g. Mount St. Helens; Glicken 1986) have created deposits which ran downslope a few tens of kilometres. These deposits transformed partly into a mudflow that moved a further few tens of kilometres. The evidence from the unbuttressed flanks of oceanic islands is even more impressive. At Hawaii in the Pacific (Moore et al. 1989) and Réunion in the Indian oceans (Lénat et al. 1990), for example, there is evidence of flank collapses that have generated debris avalanches, debris flows and turbidites which have travelled several hundreds of kilometres across the sea floor.

Since the studies around Hawaii and Réunion, evidence has been accumulating that large-scale slope failures may be a common feature in the evolution of many oceanic islands. Holcomb and Searle (1991), for example, used GLORIA side-scan sonar data to show that landslides were a feature of Tristan da Cunha and El Hierro in the Atlantic Ocean. Studies of the flanks of the Canary Islands by Watts and Masson (1995), Masson and Watts (1995), Masson (1996), Urgeles et al. (1997), Watts and Masson (1998), Gee (1999) and Urgeles et al. (1999) show widespread evidence for large-scale collapses offshore on the flanks of Tenerife, La Palma, and El Hierro. In some cases these collapses can be extended upslope into landslide valleys and head scars onshore.

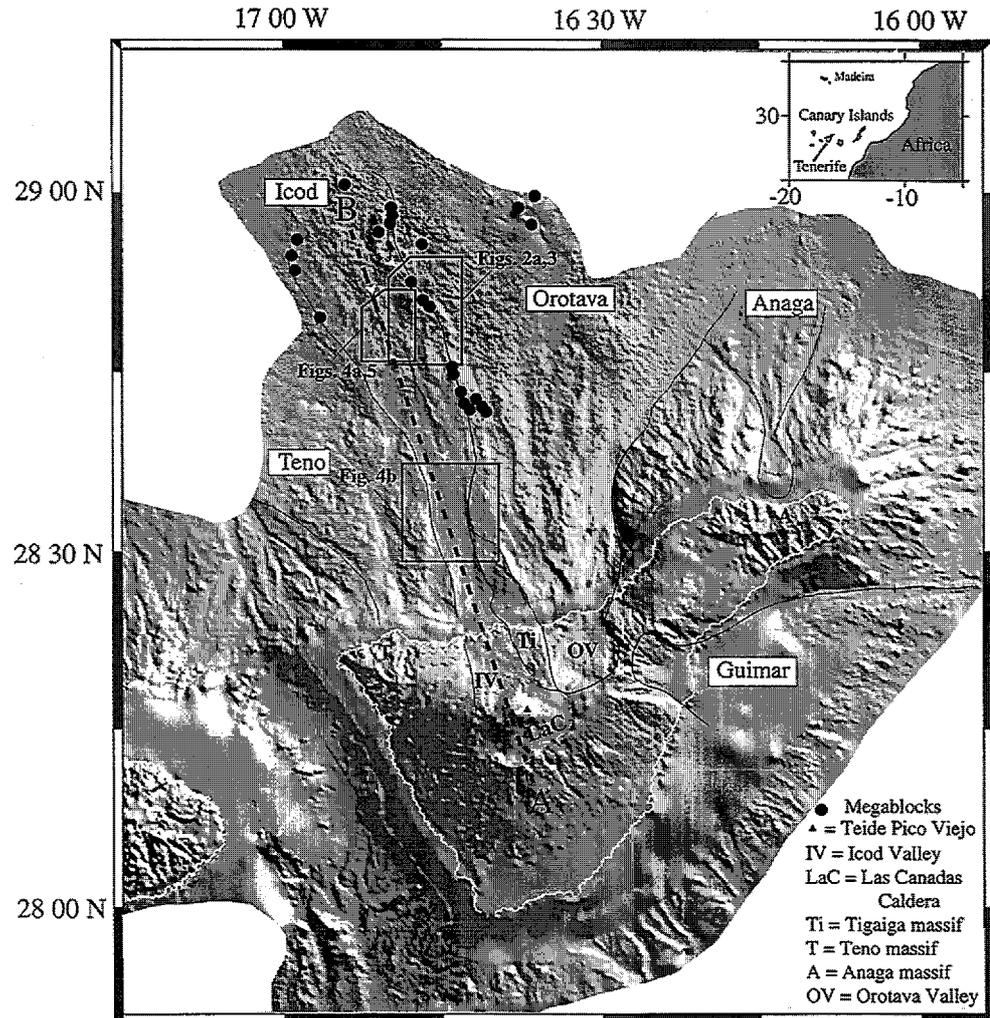
The evidence at Tenerife, the world's third highest oceanic volcano, is particularly spectacular. There, large-scale flank collapses have resulted in an unusually narrow shelf, deep submarine and sub-aerial

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Fig. 1 Plan view image of topography data in the region of Tenerife, Canary Islands. Topography onshore is based on a 1:200,000 scale Spanish military map of Tenerife (Instituto Geographica, Pers. Commun.). Topography offshore is based on swath bathymetry data acquired during *RRS Charles Darwin* cruises CD 82 and CD 108. The *grey shades* reflect the intensity of horizontal gradients of the height above and below sea level in the direction of an artificial sun at an azimuth 046° and elevation 24°. *White* is high reflectivity, *black* is low. The *thin lines* show the boundaries of the Teno, Anaga, Orotava, and Icod debris avalanches according to Watts and Masson (1998). *Thin dashed lines* indicate uncertainties in the extension of these boundaries onshore. The boundary of Guimar is based on the new Darwin data. *Heavy boxes* show the area of the TOBI images presented in Figs. 2a, 3, 4 and 5. *Arrowheads* show the direction of the perspective views in Figs. 2a and 4. *Thick dashed line* shows the location of the topography/bathymetry and summary geological cross section in Fig. 6



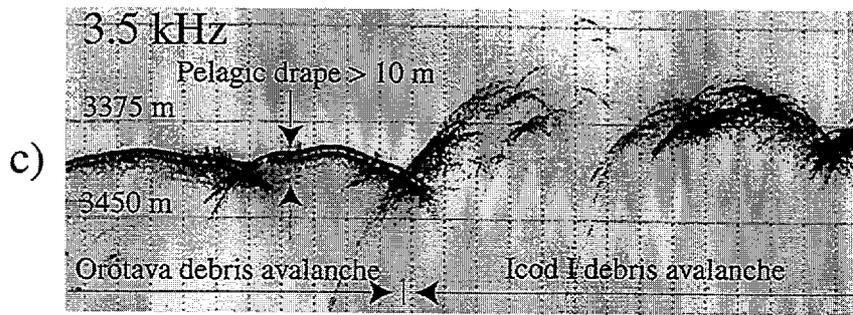
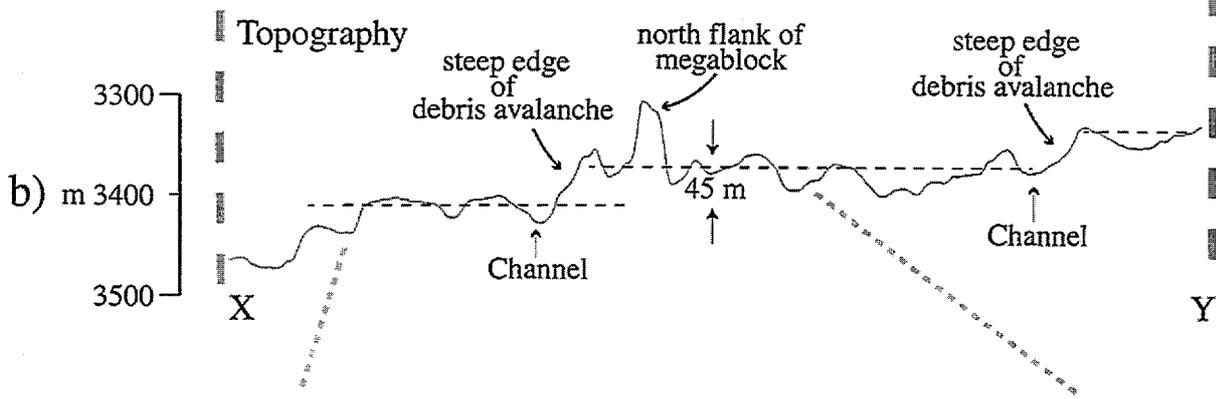
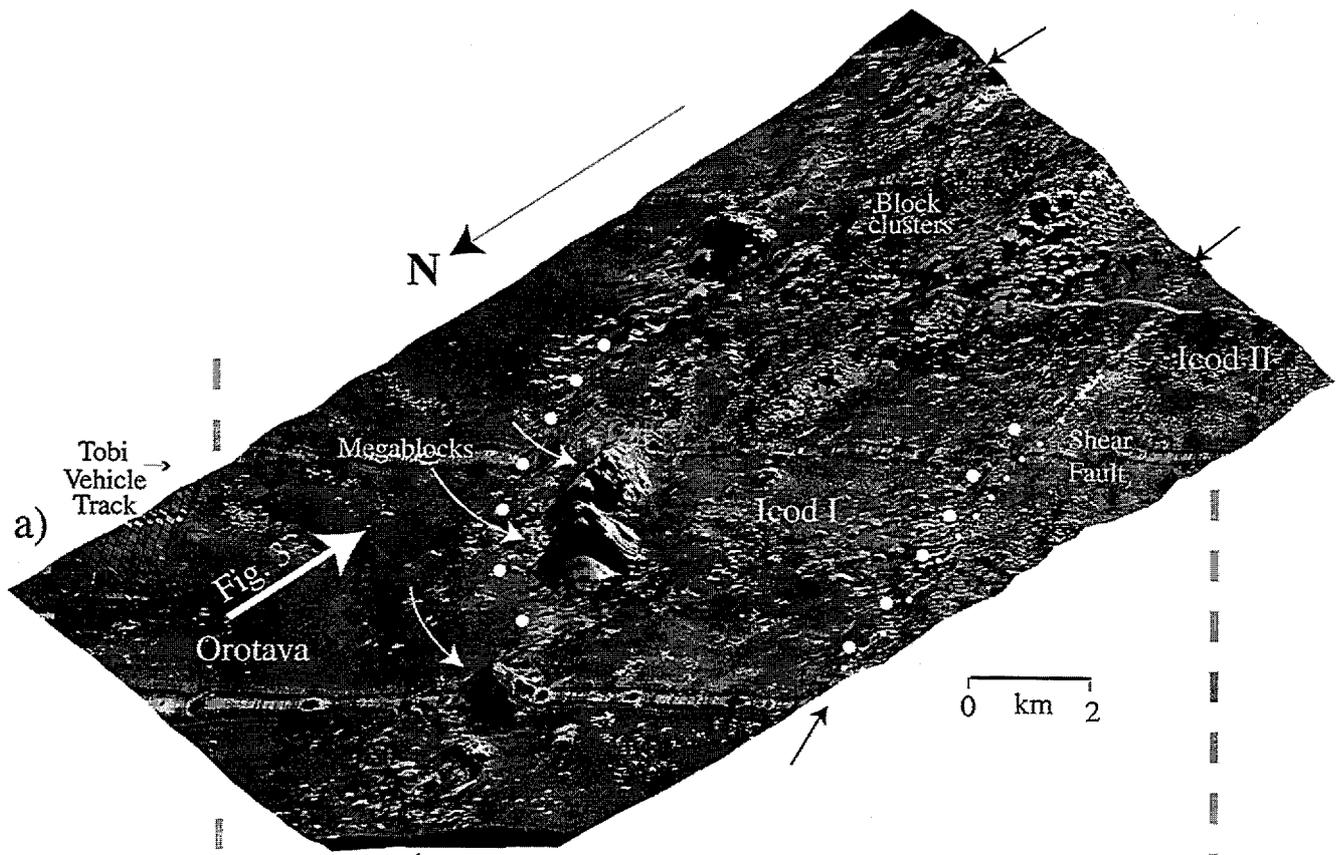
depressions and a scalloped coast line. Using backscatter derived from SIMRAD EM 12 swath bathymetry data, Watts and Masson (1998) demonstrated that the north flank of the island has been modified by at least four large-scale collapses. The two oldest collapses, Teno and Anaga, are >0.5 Ma in age and extend upslope into the Teno and Anaga massifs which together with the Roque del Conde form part of the old volcanic “core” on Tenerife (8 to 3.2 Ma; Ancochea et al. 1999). The largest landslide event, Orotava, extends onshore into the Orotava Valley and has been estimated as 0.5–0.7 Ma in age. The youngest of the events, Icod, extends upslope towards Teide which, together with Pico Viejo, forms the youngest (<150 ka; Ancochea et al. 1999) strato-volcano on Tenerife.

The Teide-Pico Viejo complex and its products fill much of Las Cañadas caldera, a striking topographic depression in the centre of Tenerife. The caldera has been interpreted as the result of either a multi-cyclic vertical collapse by Marti et al. (1994) or as the result of one or more lateral collapses of the north flank of Tenerife by Bravo (1962), Navarro and Coello (1989;

J.M. Navarro and J. Coello, unpublished data), Watts and Masson (1995) and Cantagrel et al. (1999).

In 1997 we carried out the first deep-tow side-scan sonar survey of the sea floor to the north of the Teide-Pico Viejo complex using the Southampton Oceanography Centre TOBI system. This system (Huggett and Millard 1992; Le Bas et al. 1995) is

Fig. 2a–c Sonar images of the boundary between the Icod and Orotava debris avalanches (see Fig. 1 for location). **a** Draped TOBI side-scan sonar image on the swath bathymetry. The surface of the image represents the bathymetry of the sea floor. The *grey shades* represent the intensity of the backscatter from TOBI. *White* is high backscatter, *black* is low. The Icod debris avalanche has been divided into two flows: an older one, Icod I; and a younger one, Icod II. *Large dots* show the eastern limits of the two avalanches. *Small dots* delineate shear structures within the Icod-II debris avalanche. *Arrow* indicates the direction of the more detailed perspective plot shown in Fig. 3. **b** Topographic profile along the TOBI vehicle track labelled in **a**. The boundary between Orotava and Icod I and between Icods I and II is marked by a 10-m-deep channel which is flanked by a steep slope. **c** A 3.5-kHz echo-sounder profile of a segment of the topography profile in **b**, in the region of the boundary between the Icod I and Orotava debris avalanches



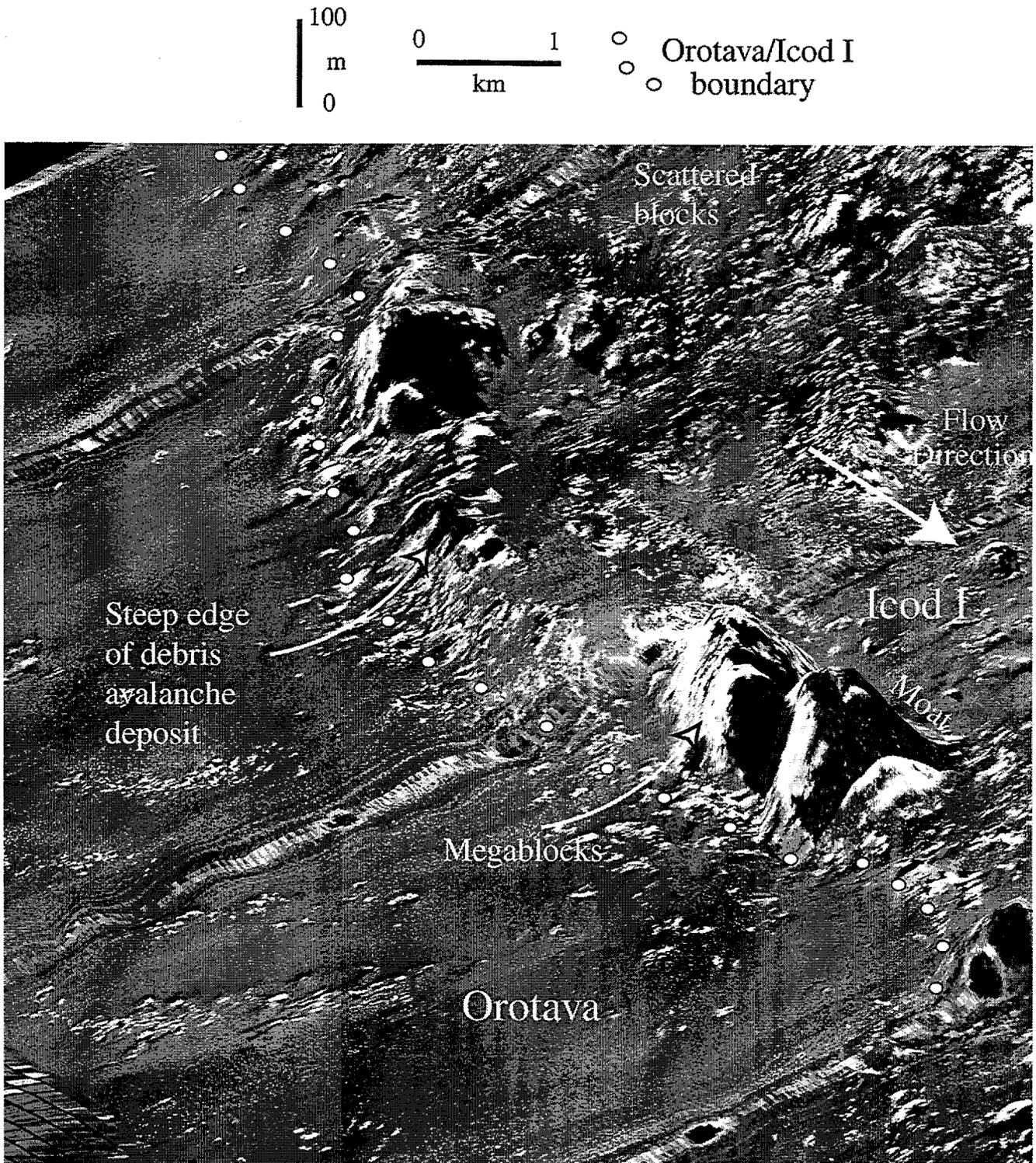


Fig. 3 Detailed sonar image of the “megablocks” at the boundary between the Icod I and Orotava debris avalanches

capable of resolving much smaller features on the sea floor than is possible with either GLORIA or SIMRAD EM 12 backscatter data and therefore has the potential to provide more detailed images of the landslide deposits than previously possible. In this study

we used the new sonar images to show that the submarine portion of Tenerife’s north flank has been subject to several phases of landslide activity in the recent past. The most recent phase, Icod, involved a significant portion of the north flank and, possibly, the summit of the older Cañadas volcanoes which precedes the Teide-Pico Viejo complex. Within a chute, located on the uppermost submarine slope in the area affected

by the Icod landslide, there is evidence for scouring and mass flow deposits (i.e. sediment waves) which post-date the Icod landslide. The upslope continuation of these deposits into the Icod valley suggest that mass wasting is an ongoing process which has already started to modify the Teide-Pico Viejo volcano itself.

Sonar data

The sonar data presented in this paper were acquired from October to November 1997 during *RRS Charles Darwin* cruise CD 108 to the westernmost Canary Islands. The *Darwin* was equipped with a hull-mounted SIMRAD EM 12 swath bathymetry system, a TOBI deep-tow side-scan sonar, 3.5- and 12-kHz echo sounders, and a "high-resolution" seismic reflection profile system. A Trimble 4000AX GPS receiver was used for navigation, which we estimate to be accurate to a few tens of metres.

While carrying out the deep-tow survey, the vessel speed was adjusted (usually between 1.5 and 2.0 knots) so as to maintain TOBI at an altitude of approximately 400 m above the sea floor. TOBI (Huggett and Millard 1992) produces acoustic images of the sea floor by transmitting 30-kHz sound pulses out to its port and starboard side and displaying the echoes that return as a function of time. The tow geometry resulted in backscatter data across a 6-km-wide swath and an acoustic "footprint" of the sea floor which varied from approximately 7×4 m near the nadir of the vehicle to approximately 42×2 m at large range.

The TOBI backscatter data was processed using techniques described by Le Bas et al. (1995). Across-track data were sampled, smoothed and gridded into 6×6-m pixels. Prior to display, each pixel was assigned a grey shade, with white indicating the highest backscatter intensity and black the lowest.

In planning the deep-tow survey, account was taken of all the existing swath bathymetry data in the region. In particular, we used the data acquired during a previous *Darwin* (CD 82; Watts and Masson 1995) and *Hesperides* cruise (Teide Group 1997) to limit the survey to the region of the Icod landslide deposit which previous work had suggested was the youngest event to have affected Tenerife's north flank. Two target areas were chosen (Fig. 1): one distal (water depths of 3.0–3.5 km) where we expected depositional features; and the other proximal (water depths of 1.1–2.5 km) where more erosional features were expected.

The Icod landslide deposit

According to Hampton and Lee (1996), terrestrial landslides are characterised by two essential features: a surface of rupture; and a displaced mass of rock and sediment. Unfortunately, little evidence exists on the

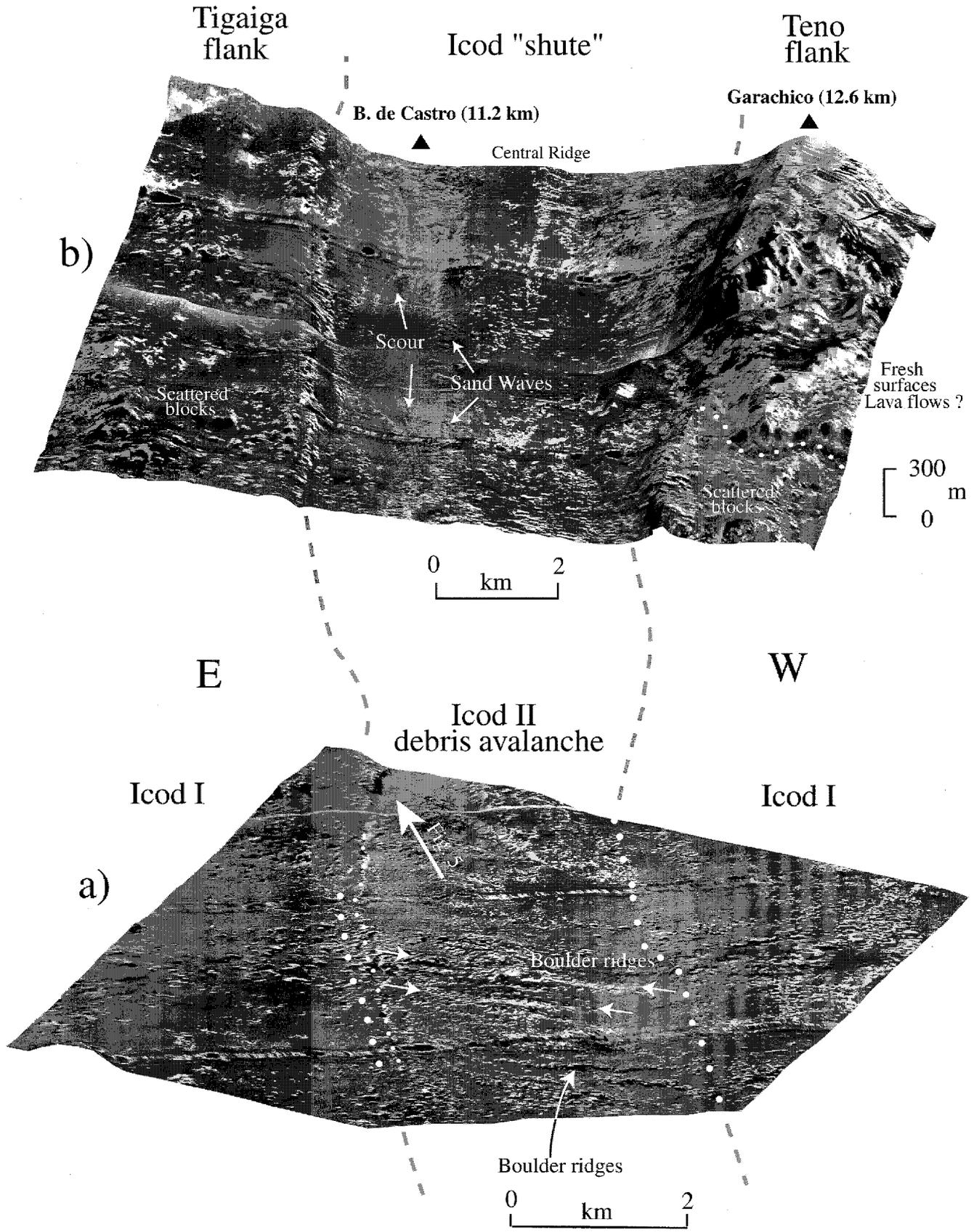
north flank of Tenerife for the actual rupture surfaces. Offshore, the blocky nature of the sea floor and the acoustic scattering that it causes makes it difficult to image the rupture surfaces in seismic reflection profile data. Onshore, however, remnants of the rupture region are preserved on the island flanks. These include "landslide" valleys with head scars (e.g. Orotava valley) some of which continue into submarine depressions on the upper slope offshore. A chaotic breccia (the "mortalón" of Bravo 1962), which may have been the source (Coello 1973) or a consequence (Navarro and Coello 1989) of landsliding, has also been encountered in water galleries.

In contrast, there is good evidence for displaced masses on Tenerife's north flank. The speckle pattern on GLORIA backscatter data (Watts and Masson 1995), for example, is indicative of numerous displaced blocks on the sea floor. Some of these deposits are associated with latitudinal (i.e. transverse) and longitudinal ridges (Watts and Masson 1995; Teide Group 1997). Moore et al. (1989) used the term "debris avalanches" to describe similar deposits around the Hawaiian Islands.

Previous studies (Watts and Masson 1998) distinguished the Icod debris avalanche from the older debris avalanches of Orotava and Anaga to the east and Teno to the west on the basis of its distinct speckle character in GLORIA and SIMRAD EM 12 backscatter data. However, the resolution of these data was generally insufficient to determine the boundaries or the details of the morphology of the deposit.

Figure 2a shows a sonar image of the Icod/Orotava boundary which was constructed by draping the TOBI backscatter data directly onto the swath bathymetry of the region. The image shows a clear distinction in the backscatter between the two debris avalanches with Icod being a region of high backscatter and Orotava one of low backscatter. These differences in backscatter are interpreted as the result of variations in the thickness of pelagic drape, with the younger avalanche of Icod having a much thinner drape than the older Orotava avalanche. Echo sounder data of 3.5 kHz (Fig. 2c) suggest that, whereas Icod has a thin or absent drape, Orotava has a drape thickness of >10 m.

In detail (Fig. 3), the Icod debris avalanche is characterised by large patches of high backscatter which are interspersed by areas of relatively lower backscatter. Most of the high backscatter correlate with bathymetric highs, and we interpret these regions as clusters of displaced blocks. The blocks within Icod typically range in size from a few metres to a few tens of metres. The origin of the low backscatter regions is less clear, but we speculate that they are indicative of a smoother sea floor that is made up of finer-grained material. One possibility is that the low backscatter regions represent a "matrix" of rock fragments. These areas of relatively low topography between blocks may also have been areas of preferential settlement of



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Fig. 4a, b Draped TOBI side-scan sonar images on the swath bathymetry of the Icod debris avalanche. **a** Distal region of Icod II showing the boulder ridges. *Large dots* show the boundary with the Icod I debris avalanche. *Small dots* delineate shear structures near the edge of the flow. *Arrows* indicates the direction of the more detailed perspective plot shown in Fig. 5. **b** Proximal region of Icod II showing the Icod shute. The shute is a 5-km-wide morphological depression of >100 m which is characterised by a diffuse region of high and low backscatter in its uppermost regions and a distinct speckle pattern in its lowermost regions. The shute is characterised by scour features and sand waves

a finer-grained “turbidite” cloud that was associated with avalanche emplacement, as well as post-emplacment sedimentation.

Along the eastern margin of Icod, there are a few very large blocks (labelled “megablocks” in Figs. 2a and 3). The three largest blocks have widths of 0.9–1.2 km, lengths of 1.2–1.7 km and stand approximately 140–250 m above the mean depth of the surrounding sea floor. The blocks are highly angular with pointed tops, and there is evidence (Fig. 3) that they have very rough, possibly striated, surfaces. The occurrence of large blocks at the edge of the flow is a relatively common feature of rapidly moving sub-aerial landslides where they are dubbed “lateral deposits” (Johnson 1970; Iverson 1997); however, they are not a common feature of previous sonar surveys of submarine debris avalanches.

The long axis of the large blocks at the edge of the Icod debris avalanche appear to be aligned in the direction of the flow, suggesting that they were transported during the same flow pulse. Flanking the blocks are small topographic depressions (labelled Moat in Fig. 3) which may result from the weight of the blocks which, once the flow ceased, caused them to sink into the soft underlying sediment, thus producing the depressions.

The surface of the Icod debris avalanche is locally up to 45 m shallower than the older Orotava debris avalanche (Fig. 2b). The boundary region is characterised by a topographic depression in Orotava (Fig. 2b) and a sharp deposit margin to Icod (Fig. 3). Similar features have been described from the margins of the El Golfo debris avalanche offshore El Hierro (Masson et al. 1998) and on the Saharan debris flow (Masson et al. 1993), as well as numerous sub-aerial flows (Johnson 1970). The fact that Icod maintains such a steep slope at its margin has implications, we believe, for the physical properties of the flow.

The western boundary of Icod is also associated with several clusters of small displaced blocks. Although large blocks are rarer than on the eastern margin, a few are still seen, notably including one very large block (latitude 28° 49.7' N and longitude 16° 56.6' W) which is 2.0 km long, 1.3 km wide and >200 m high. The wide separation of the blocks makes

it difficult to locate the western boundary of the Icod debris avalanche with precision; however, topographic profiles show that the surface of the Icod deposit is locally up to 100 m shallower than Teno, and in places its western edge maintains a similar sharp deposit margin as does the eastern edge.

The central region of the Icod debris avalanche is characterised by two flow-parallel linear features, each of which is characterised by a strongly aligned speckle pattern on TOBI images (Fig. 4a). The easternmost feature correlates with a topographic high and several en echelon 10-km-long depressions of the sea floor with widths of up to 0.8 km and depths of up to 10 m. In places (e.g. Fig. 5), the depressions appear asymmetrical with steep edges. The long-axes of the depressions are aligned in the flow direction and we speculate that they may be “pull-apart” features that formed in response to small amounts of extension on flow parallel shears at the edge of the flow. The westernmost feature, however, does not appear to have any topographic expression.

Between the two flow-parallel features, the distinctive morphology and backscatter character of the sea floor suggests that the central region of Icod may be a separate flow with a different emplacement mechanism. Probably the most striking features are the “boulder ridges” (Fig. 4a) which trend nearly perpendicular to the main flow direction. Each ridge is approximately 2–3 km in length, 500 m wide and up to approximately 10 m high. The ridge crests have a distinct speckle pattern in the backscatter data suggesting that they are made up of numerous small blocks. Between individual ridges the sea floor is much smoother. We believe that the boulder ridges are probably “pressure ridges” similar to those described by Plafker and Ericksen (1978) in sub-aerial debris flows. The concentration of coarse material at the surface of the ridges is due to the fine-grained matrix having “drained away” from these topographically high areas in the final stages of the flow.

The region between the two flow-parallel features is topographically higher than the rest of the Icod debris avalanche (e.g. Fig. 2b). This observation, together with the distinct morphology and backscatter character, suggest that the region between and, probably, including the shear structures represent the deposits of a younger flow deposit; however, we cannot determine from the sonar data how much younger the central part of the flow might be, relative to the main Icod debris avalanche. Because of its location within the central part of Icod, its distinct morphology and the possibility that it might represent a young, if not the youngest, part of the flow, we designate this flow (e.g. Figs. 2a, 3, 4a) “Icod II” in order to separate it from the rest of the flow, Icod I.

Upslope of Icod II is a striking sea-floor depression or “shute”. Swath bathymetry data show that the shute is approximately 5 km wide, >100–200 m deep and resembles in structure a steep-sided “graben”.

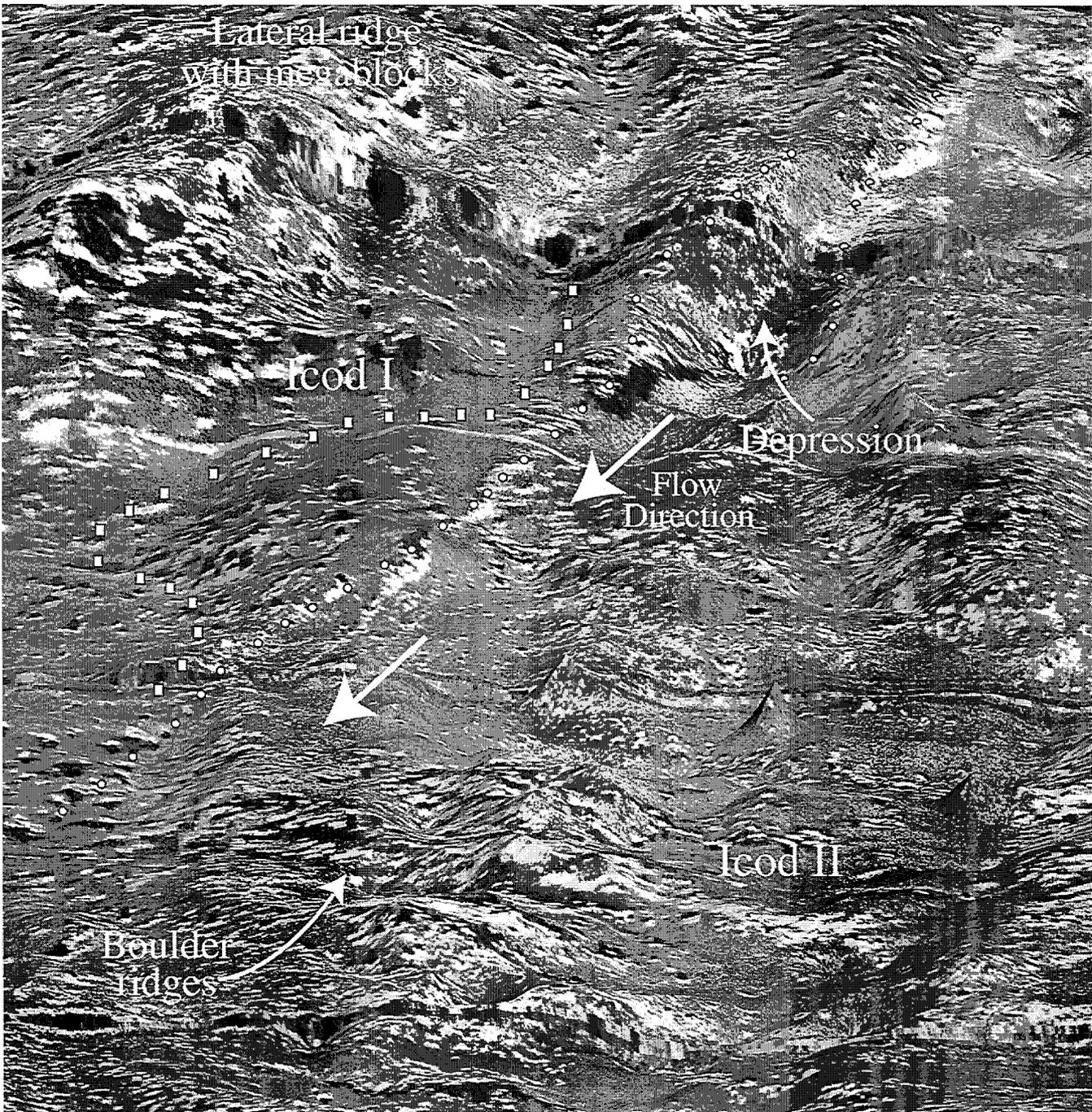
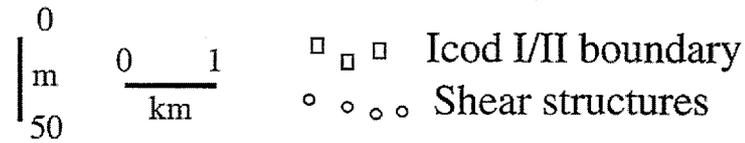


Fig. 5 Detailed sonar image of the shear structures and topographic depressions at the eastern boundary between the Icod-I and Icod-II debris avalanches

The eastern flank of the shute extends upslope into the Tigaiga massif, whereas the western flank continues upslope into the region between the Icod Valley and the Teno massif.

The draped TOBI images (e.g. Fig. 4b) show that the shute is generally a region of high backscatter. The pattern of backscatter differs, however, from elsewhere within the Icod debris avalanche. It lacks the pervasive speckle pattern that is characteristic of Icods I and II. Instead, it is more diffuse with large interspersed regions of high and low. Within the shute,

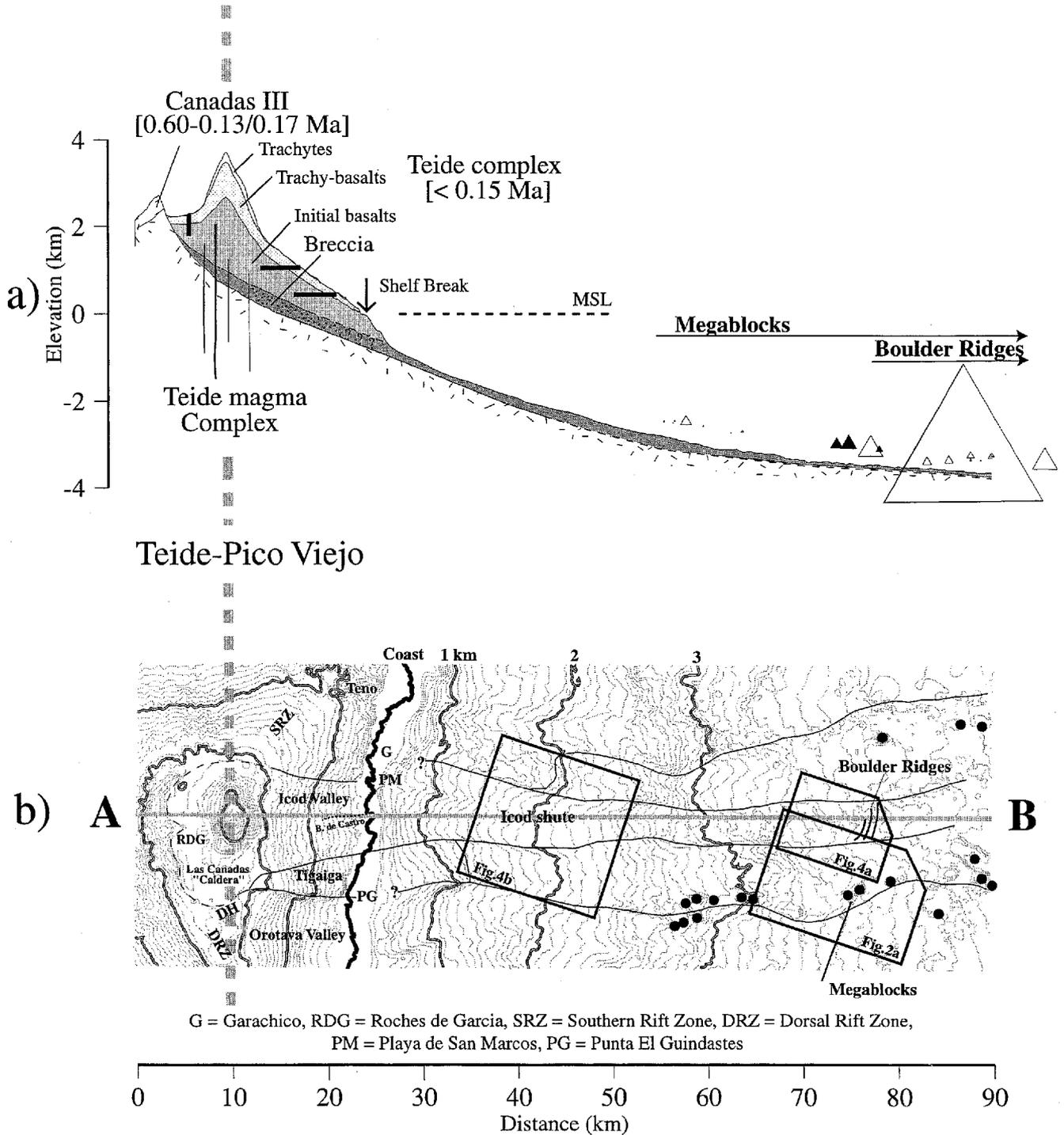


Fig. 6a, b Topography of the Icod debris avalanche showing its upslope continuation into the Icod Valley and the Teide-Pico Viejo complex. **a** Profile AB (Fig. 1) of the southern wall of the Cañadas caldera, the Icod valley and the Icod debris avalanche. Geological cross section is based on Fig. 16A in J.M. Navarro and J. Coello (unpublished data). *Thick horizontal line* shows the approximate length of a representative water gallery. The *open triangles* show the projected positions of the blocks in Icod I and the size of the triangles reflect their relative sizes. *Filled triangles* show the three "megablocks" imaged in Figs. 2a and 3. The *question marks* indicate uncertainties in the correlation

between the chaotic breccias onshore and the landslide deposits offshore. **b** Detailed topography of the north flank of Tenerife in a 15-km-wide "swath" either side of profile AB. Contour interval=100 m, except in water depths >2500 m where it is 50 m. The *boxes* indicate the location of the draped images in Figs. 2a and 4. *Dots* show the locations of the "megablocks". *Lines* indicate the boundaries of the Icod debris avalanche and its continuation into the Icod Valley onshore. *Dashed lines* indicate uncertainties in the extension of the boundaries upslope into Las Cañadas caldera

there are some lineated features in the backscatter data which trend sub-parallel to its steep edge. We interpret these features as the products of scour. To the west of these features, a band of sediment waves is seen. Individual waves trend perpendicular to the edge of the shute.

The backscatter character of the flanks of the shute differ from that of its central region. The eastern flank has a distinct speckle pattern that resembles the Icod-I debris avalanche. A similar speckle pattern characterises the deeper-water parts of the western flank. Most of the western flank, however, is characterised by much larger patches of high and low backscatter than is typical of debris avalanche deposits. The uppermost western edge of the shute extends upslope, intersecting the Tenerife coast near La Garachico. In 1706 the town's harbour was infilled by a lava flow that had travelled from the cone of Montaña Negra down the northwestern flank of Teide. The unusual backscatter pattern might represent fresh lava flows on the sea floor. Alternatively, it might indicate rock outcrop related to erosion by one or more of the debris avalanches.

Discussion

The Icod debris avalanche and the evolution of the Cañadas volcanoes

The region of the Icod debris avalanche extends upslope, intersecting the northern coast of Tenerife between Playa de San Marcos and Punta El Guindastes (Fig. 6). Within this region are the Icod Valley and the Tigaiga massif, at the head of which is the Teide-Pico Viejo complex. Because the entire region is covered by younger eruptive material, there is no obvious field evidence for rupture surfaces which could be associated with the avalanche deposit; however, there is evidence from water galleries of a chaotic breccia deposit that underlies much of the Icod Valley and the Tigaiga massif region (Navarro and Coello 1989, J.M. Navarro and J. Coello, unpublished data). The problem is that clasts in the breccia yield a wide range of ages (Ancochea et al. 1999); thus, it is difficult to attribute the deposit to a particular debris avalanche event. However, taking all the evidence into account, we follow Navarro and Coello (1989, J.M. Navarro and J. Coello, unpublished data) in interpreting the Icod Valley as a landslide valley. The close spatial relationship between the Icod Valley and the Icod debris avalanche leads us to link the two areas as source and deposit for the landslide.

The young eruptive material that now fills the Icod Valley represents the products of the Teide-Pico Viejo complex. The fact that the complex has been constructed within the Las Cañadas caldera, which has been subject to repeated episodes of vertical and probably lateral landslides, suggests a strong link

between landsliding and caldera collapse (Marti et al. 1997; Ablay and Kearey 2000). Furthermore, the scalloped horseshoe trace of the caldera wall, of which only the southern side exists, bears a striking resemblance to the head scars of large landslides (Cantagrel et al. 1999). We therefore believe that a segment of the caldera wall – if not the actual rupture surface – was most probably part of the rupture zone that generated the Icod debris avalanche.

The youngest of the deposits in the caldera wall which has been unambiguously offset by vertical movements is the Diego Hernández formation (Marti et al. 1990). This formation represents the uppermost of several sequences of basalts, trachybasalts and phonolites which together form the edifice of the Cañadas volcanoes. Recent age dating (Ancochea et al. 1999) suggest that the edifice was constructed *prior to* the Teide-Pico Viejo complex in several distinct phases which began 3.5–2.6 Ma and ended 1.1–0.17 Ma. At the present day, outcrops of the products of the edifice are limited to the Tigaiga massif and to the southwestern and southeastern flanks of Tenerife.

We believe, on the basis of the deposit character, elevation relative to adjacent avalanche deposits and lack of a significant pelagic drape, that Icod is probably the youngest of the debris avalanches that were generated by the collapse of the Cañadas edifice. The actual age of Icod is, however, uncertain. The drape thickness, for example, is small but varies too much within the avalanche region to be a reliable age indicator. Moreover, there are no dates available yet for the Teide lavas which immediately overlie the chaotic breccia beneath the Icod valley. However, if we follow Cantagrel et al. (1999) and assume that the eastern sector of the caldera wall is the head scar to Icod, then the age of the youngest formation that has been offset in this sector provides a constraint on the age of this landslide event. Recent age dating (Ancochea et al. 1999) suggests that the youngest part of the Diego Hernández Formation in the eastern wall is approximately 0.17 Ma, which would be a maximum age for the most recent landslide to have modified Tenerife's north flank. As Masson and Watts (1995) point out, this age is in agreement with the age of turbidite "g" in the Madeira Abyssal Plain which is volcanoclastic in origin and has been sourced to Tenerife or one of the other eastern Canary Islands.

According to Cantagrel et al. (1999), as much as 700–850 km³ of material is now missing from the edifice of the Cañadas volcanoes. Assuming that Icod is 15–20 km wide, 65 km long and 45–100 m higher than flanking debris avalanches, then as much as 44–130 km³ of material was transported by this avalanche. This is a *minimum* estimate because it does not include deposits, particularly turbidites, beyond the edge of the survey area, which, although thin, may have been spread out over very large areas. Irrespective of this, these volume estimates are large and suggest that the Icod landslide event played a major role

in the mass wasting of the Cañadas volcanoes. The large size of some of the blocks that characterise the Icod deposit suggest that the event excavated large sectors of the flank and, possibly, the summit of these volcanoes. The "drop zone" (e.g. Fig. 6) of the largest blocks is in water depths of >3400 m, which, assuming that the Cañadas volcanoes occupied a similar position to what the Teide-Pico Viejo complex does presently, would have been >60 km from the present-day volcano summit.

We have shown that the Icod landslide can be divided into two morphological provinces, Icod I and Icod II, with the possibility that Icod II is a younger landslide event than Icod I. The Icod-II deposit, like Icod I, maintains a steep eastern edge (e.g. Fig. 2b), and there is evidence that it is approximately 20–30 m higher than Icod I; however, there is no obvious step in topography at its western boundary. In distal areas, Icod II is characterised by the development of numerous boulder ridges, but blocks of a large size are absent. In proximal areas of Icod II, erosional features appear to dominate over depositional ones.

Our data show that the morphology and character of the Icod-I and Icod-II debris avalanches are sufficiently different to suggest that they are two separate flows. In particular, the large blocks found in Icod I are lacking in Icod II, and the flow structures found in Icod II are absent in Icod I; however, the available evidence, although limited, does not suggest more than one collapse event. We believe therefore that the most likely scenario is one in which both flows are part of a single complex lateral collapse of the edifice of the Cañadas volcano.

Flow mechanisms

Although we lack quantitative data on the flow composition, velocity and thickness that are used to constrain the rheology of debris avalanches onshore (e.g. Voight and Sousa 1994), there are certain observations that can be made about the morphology of the Icod submarine debris avalanche deposits that might, in the future, provide a framework with which to compare the behaviour of terrestrial and submarine landslides.

The first concerns the efficiency of the submarine deposits. The Icod debris avalanche, as imaged by the sonar data, extends into at least 3.6 km of water (Fig. 2). The deposit is approximately 70 km from the summit of Teide-Pico Viejo complex which itself is 3.7 km above sea level. Assuming that the Cañadas volcanoes were no higher than 3.0 km (Arãna 1971) and occupied a similar location to Teide, then the horizontal runout distance of the avalanche deposit (L) is 70 km and the vertical drop (H) is $3.6+3.0=6.6$ km. The equivalent friction coefficient (H/L) of 0.09 thus represents a very high efficiency flow. Whereas this value is similar to that observed for debris avalanches on the flanks of Hawaii and other oceanic islands (e.g.

Hampton and Lee 1996), it is smaller than is typical for sub-aerial debris flows (i.e. the avalanche is more efficient). In a wider context, it is an order of magnitude larger (i.e. less efficient) than the typical value for the long run-out debris flows that originate on passive continental margins.

Whereas its efficiency may have been high, at least in comparison with sub-aerial debris flows, the long-term strength of the flow material must have been high enough to maintain the steep deposit margins. The observations of hummocky topography and pull-apart structures also suggest a highly viscous "slurry" type flow that was composed of material with a finite yield stress.

Recently, several models have been constructed for sub-aerial debris avalanches (e.g. Voight and Sousa 1994) which might also explain our observations. These include models in which the behaviour of debris avalanches are modelled as a Bingham material, as suggested by Johnson (1970). Such a material behaves as an elastic body for stresses that are less than the yield point, and for greater stresses gives a steadily increasing strain. Unfortunately, constraints on the parameters (e.g. Young's Modulus, viscosity and yield stress) which describe the behaviour of a Bingham material are not possible from our data.

Differences in the character and morphology of the Icod-I and Icod-II deposits suggests that the two flows may have had significantly different emplacement mechanisms, and thus probably different rheologies. The chaotic, blocky nature of Icod I, lacking preservation of flow-related structures, is very typical of catastrophic submarine debris avalanche deposits (e.g. Moore et al. 1989; Lénat et al. 1990; Masson 1996). In contrast, the preservation of flow-related structures, such as boulder ridges and shears within the Icod-II deposit, suggests a debris flow emplacement mechanism, with a more coherent and perhaps less catastrophic flow mechanism. One possibility is that Icod I represents the product of the initial collapse of the flank and, possibly, the summits of the Cañadas volcanoes, whereas Icod II results from continuing failure of the internal volcano structure due to the unbuttreasing effects of the initial collapse.

The Teide-Pico Viejo complex and ongoing mass-wasting processes

The Icod-II debris avalanche deposit can be traced upslope into a submarine shute. Swath bathymetry data indicate that the shute continues upslope, intersecting the Tenerife coast in the region of the Icod Valley.

Presently, the Icod Valley is drained by several fluvial valleys – or barrancos – two of which appear to drain directly into the shute. Indeed, sediments delivered by the barrancos may be the source of the mass flows responsible for both the scour and the sediment

waves that are now observed in the shute. If this is correct, then it suggests that these erosional and depositional features are younger than Icod and, probably, younger than the Teide Pico-Viejo complex itself.

The evidence for some form of sediment transport within the shute suggests that mass wasting of the Teide-Pico Viejo strato-volcano has already begun. This is of interest because age dating (Ancochea et al. 1999) suggests that the Teide-Pico Viejo complex only formed during the past 0.15 Ma. The long history of landslides on Tenerife's north flank, its high elevation and the fact that at least part of Icod valley is underlain by a chaotic breccia suggest that mass wasting is part of an ongoing process which eventually, we believe, will lead to the collapse of the Teide-Pico Viejo complex itself.

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References

- Ablay GJ, Kearey P (2000) Gravity constraints on the structure and volcanic evolution of Tenerife, Canary Islands. *J Geophys Res* 105:5783–5796
- Ancochea E, Huertas MJ, Cantagrel JM, Coello J, Fuster JM, Arnaud N, Ibarrola E (1999) Evolution of the Canadas edifice and its implications for the origin of the Canadas caldera (Tenerife, Canary Islands). *J Volcanol Geotherm Res* 88:177–199
- Araña V (1971) Litología y estructura del Edificio Canadas, Tenerife. *Estudios Geol* 27:95–135
- Bravo T (1962) El circo de Las Canadas y sus dependencias. *Bol Esp Hist Nat* 60:93–135
- Cantagrel JM, Arnaud NO, Ancochea E, Fuster JM, Huertas MJ (1999) Repeated debris avalanches on Tenerife and genesis of the Las Canadas Caldera wall (Canary islands). *Geology* 27:739–742
- Coello J (1973) Las series volcánicas en subsuelos de Tenerife. *Estudios Geol* 29:491–512
- Gee M (1999) The collapse of oceanic islands and the mechanics of long runout debris flows: examples from the NW African margin. PhD thesis, Oxford University
- Glicken H (1986) Rockslide–debris avalanche of May 18, 1980, Mt. St. Helens Volcano, Washington. PhD thesis, University of California
- Hampton MA, Lee HJ (1996) Submarine landslides: reviews of *Geophysics* 34:33–59
- Holcomb RT, Searle RC (1991) Large landslides from oceanic volcanoes. *Mar Geotechnol* 10:19–32
- Huggett QJ, Millard NW (1992) Towed ocean bottom instrument TOBI: a new deep-towed platform for side-scan sonar and other geophysical surveys. In: 24th Annual Oceanology Technology Conference, Houston, Texas, pp 349–354
- Iverson RM (1997) The physics of debris flows. *Rev Geophys* 35:245–296
- Johnson AM (1970) Physical processes in geology. Freeman, San Francisco, pp 1–577
- Le Bas TP, Mason DC, Millard NC (1995) TOBI image processing: the state of the art. *J Oceanic Eng* 20:85–93
- Lénat J-F, Bachèlery P, Bonneville A, Galdéano A, Labazuy P, Rousset D, Vincent P (1990) Structure and morphology of the submarine flank of an active basaltic volcano: Piton de la Fournaise (Réunion island, Indian ocean). *Oceanol Acta* 10:211–224
- Marti J, Mitjavila J, Villa IM (1990) Stratigraphy and K–Ar ages of the Diego Hernandez wall and their significance on the Las Cañadas caldera formation (Tenerife, Canary Islands). *Terra Nova* 2:148–153
- Marti J, Mitjavila J, Araña V (1994) Stratigraphy, structure and Geochronology of the Las Cañadas Caldera (Tenerife, Canary Islands). *Geol Mag* 131:715–727
- Marti J, Hurlimann M, Ablay GJ, Gudmundsson GJ (1997) Vertical and lateral collapses on Tenerife (Canary Islands) and other volcanic ocean islands. *Geology* 25:879–882
- Masson DG (1996) Catastrophic collapse of the volcanic island of Hierro 15 ka ago and the history of landslides in the Canary Islands. *Geology* 24:231–234
- Masson DG, Watts AB (1995) Slope failures and debris avalanches on the flanks of volcanic oceanic islands—the Canary Islands, off NW Africa. *Landslide News* 9:21–24
- Masson DG, Huggett QJ, Brunnsden D (1993) The surface texture of the Saharan debris flow deposit and some speculations on submarine debris flow processes. *Sedimentology* 40:583–598
- Masson DG, Canals M, Alonso B, Urgeles R, Huhnerbach V (1998) The Canary debris flow: source area, morphology and source mechanisms. *Sedimentology* 45:411–432
- Moore JG, Clague DA, Holcomb RT, Lipman PW, Normark WR, Torresan ME (1989) Prodigious submarine landslides on the Hawaiian Ridge. *J Geophys Res* 94:465–484
- Navarro JM, Coello J (1989) Depressions originated by landslide processes in Tenerife. In: ESF Meeting on Canarian Volcanism, Lanzarote, pp 150–152
- Plafker G, Ericksen GE (1978) Nevados Huascarán avalanches. In: Voight B (ed) *Rockslides and avalanches*, vol 1. Natural phenomena. Elsevier, Amsterdam, pp 277–361
- Teide Group (1997) Morphometric interpretation of the northwest and southeast slopes of Tenerife, Canary Islands. *J Geophys Res* 102:487–498
- Urgeles R, Canals M, Baraza J, Alonso B, Masson D (1997) The most recent megalandslides of the Canary Islands: El Golfo debris avalanche and Canary debris flow, West El Hierro Island. *J Geophys Res* 102:305–323
- Urgeles R, Masson DG, Canals M, Watts AB, Le Bas TP (1999) Recurrent large-scale landsliding on the west flank of La Palma, Canary Islands. *J Geophys Res* 104:331–348
- Voight B, Sousa J (1994) Lessons from Ontake-san: a comparative analysis of debris avalanche dynamics. *Eng Geol* 38:261–297
- Watts AB, Masson DG (1995) A giant landslide on the north flank of Tenerife, Canary Islands. *J Geophys Res* 100:487–498
- Watts AB, Masson DG (1998) Reply (to comment on “A giant landslide on the north flank of Tenerife”, Canary Islands by J. Marti). *J Geophys Res* 103:9949–9952
- Wessel P, Smith WHF (1991) Free software helps map and display data. *EOS Trans Am Union* 72:441–446