



# Flank collapse and large-scale landsliding in the Cape Verde Islands, off West Africa

**D. G. Masson and T. P. Le Bas**

*National Oceanography Centre, University of Southampton, European Way, Southampton SO14 3ZH, UK  
(dgm@noc.soton.ac.uk)*

**I. Grevemeyer and W. Weinrebe**

*IFM-GEOMAR, Wischhofstrasse 1-3, D-24148 Kiel, Germany*

[1] Large-scale landslides occur on the flanks of many volcanic oceanic islands worldwide. None have taken place in historical time, but their geohazard potential, especially their ability to generate tsunamis, is large. The Cape Verde Islands are a group of 10 large and several smaller volcanic islands off the coast of West Africa between 15 and 17°N. A single flank landslide has previously been described from the island of Fogo, but systematic analysis of the Cape Verde group has until now been lacking. This paper describes and interprets a multibeam bathymetry data set covering the slopes of the western Cape Verde Islands, including those of the islands with the most recent volcanic activity, Fogo in the southwest, and Santo Antao in the northwest. All of the larger islands show evidence of large flank landslides, although only Fogo and the southwest part of Santo Antao have failed in the last 400 ka. Tope de Coroa, the volcano at the southwest end of Santo Antao, has been inactive for the past 170 ka and is judged to have a low landslide potential unless volcanic activity resumes. In contrast, there would seem to be a high probability of a future east directed landslide on Fogo, from the area of the highly active Pico do Fogo volcano, although it is impossible to predict a timescale for such an event. A tsunami generated by such a landslide could have a catastrophic effect on the adjacent island of Santiago and possibly even farther afield on the West African coast.

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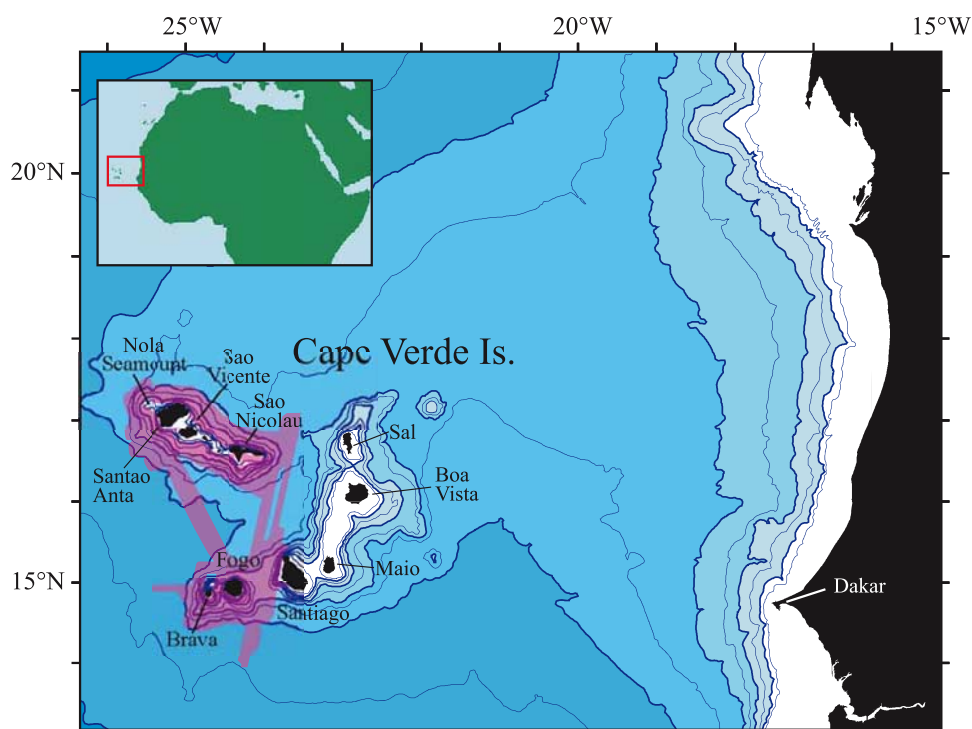
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## 1. Introduction

[2] Evidence for flank collapse and large-scale landsliding (hereafter referred to as landslide or landsliding) is preserved on many volcanic ocean islands worldwide (Canary Islands [Masson, 1996;

Masson *et al.*, 2002; Watts and Masson, 1995], Hawaii [Moore *et al.*, 1989, 1994], Reunion [Labazuy, 1996; Ollier *et al.*, 1998], Cape Verde Islands [Day *et al.*, 1999]). Large landslides incorporating tens of km<sup>3</sup> of rock are, however, rare events even on geological timescales, and no



**Figure 1.** Map showing the regional setting of the Cape Verde Islands. Magenta shaded area shows area of multibeam bathymetry coverage. Inset shows location off West Africa at 15° to 17°N.

events larger than about 5 km<sup>3</sup> are known to have occurred in historical time [Ward and Day, 2003]. The geohazard potential of a large volcanic island landslide is thus poorly constrained by observation, although all authors agree that, in addition to local destruction on the island, such an event is likely to have considerable tsunamigenic potential [Mader, 2001; Masson et al., 2006; McMurtry et al., 2004; Ward and Day, 2001]. It is thus important that all oceanic islands likely to be affected by landslides are subjected to geohazard assessment. Here we evaluate the geomorphology of the submarine slopes of the Cape Verde Islands and assess which areas have been affected by landslides in the geological past. A brief assessment of future geohazard potential is also included.

## 2. Location and Geological Setting

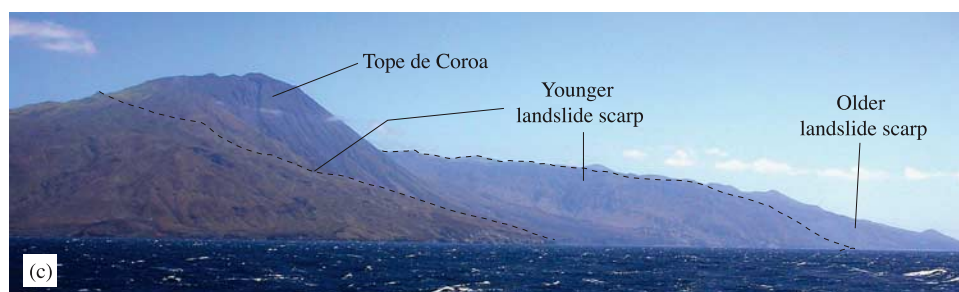
[3] The Cape Verde Islands are a horseshoe-shaped group of volcanic islands located 550–800 km off the West African coast between 15° and 17°N (Figure 1). They are the culmination of the Cape Verde Rise, an area of elevated seafloor over 1000 km across, interpreted as the topographic expression of an underlying mantle plume [Holm et al., 2006; McNutt, 1988]. The islands show only a weak age progression from east to west, reflecting

the near stationary nature of the African plate is with respect to the underlying mantle [Holm et al., 2006]. Many of the islands show overlapping periods of active volcanism, although Sal and Maio in the east have the oldest dated volcanic rocks (12 and 16 Ma, respectively) and only Fogo and Santo Antao, at the western ends of the northern and southern arms of the “horseshoe,” respectively, have experienced significant volcanism in the last 500 ka [Holm et al., 2006; Plesner et al., 2002]. Fogo is entirely covered in young volcanic rocks and “may be entirely Quaternary in age” [Holm et al., 2006].

[4] Prior to the work carried out in this study, landslides had only been reported from Fogo [Day et al., 1999; Le Bas et al., 2007]. Here, a single landslide is seen on the eastern flank of the island (Figure 2a). It is partially filled by volcanic products from the Pico do Fogo volcano, a highly active volcanic center that has erupted, on average, every 20 years since the islands were discovered by European explorers some 500 years ago [Fonseca et al., 2003; Torres et al., 1998].

## 3. New Data

[5] The data described in this paper consist of multibeam bathymetry and acoustic backscatter

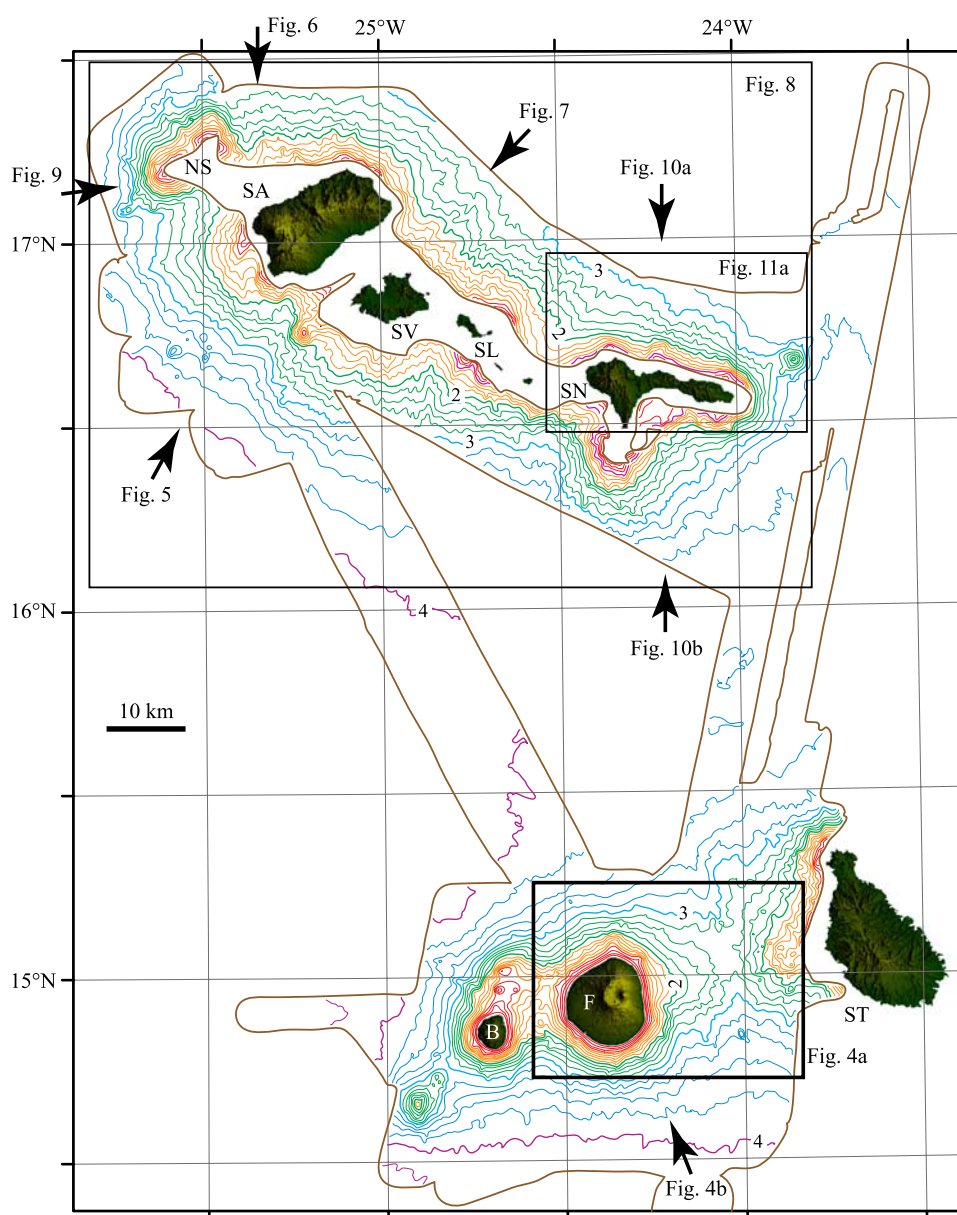


**Figure 2.** Photographs of (a) Pico do Fogo from the east with the Monte Amarelo landslide scarp in the background. The semicircular landslide scarp on Fogo is about 9 km in diameter and up to 1 km high. (b) the Monte Amarelo landslide scarp viewed from inside the landslide scarp (partially filled with young volcanic rocks). (c) Santo Antao from the southwest. The inner landslide scarp (its top denoted by dashed line) surrounding the Tope de Coroa volcano on Santo Antao is about 6 km across.

images. Multibeam bathymetry and backscatter data were collected using an Atlas Hydrosweep system on R/V *Meteor* cruise 62/3 and a Simrad EM 12 system on RRS *Charles Darwin* cruise 168. Multibeam coverage extends along both flanks of the northern island chain from Sao Nicolau in the

east to Santo Antao in the west (Figure 3). For the southern island chain, the western flank of Santiago and the area around Fogo and Brava were surveyed. No data were collected around the eastern islands of Sal, Boavista and Maio. Marine data were combined with NASA Shuttle Radar Topog-





**Figure 3.** Summary of multibeam data from the western Cape Verde Islands. Contour interval 200 m. Boxes show locations of later plan view figures. Arrows show view direction of 3-D figures. NS, Nola Seamount; SA, Santo Antao; SV, Sao Vicente; SL, Santa Luzia; SN, Sao Nicolau; ST, Santiago; F, Fogo; and B, Brava.

raphy Mission (SRTM) data from the islands, allowing correlation of onshore and offshore structures.

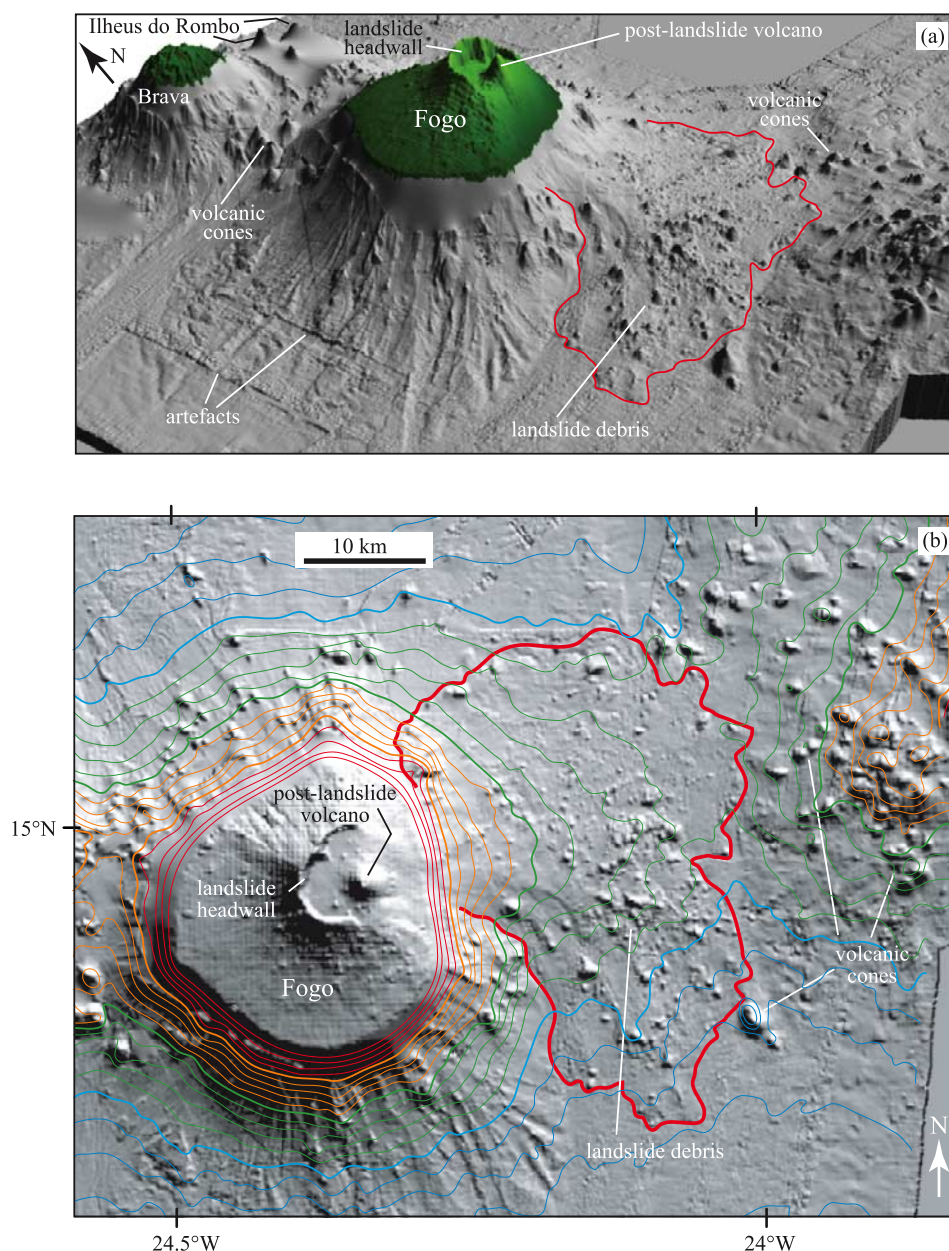
## 4. Bathymetry and Backscatter Interpretation

### 4.1. Fogo, Brava, and the Western Flank of Santiago

[6] The island of Fogo is dominated by the Pico do Fogo volcano, rising over 2800 m above sea level

(Figures 2a, 2b, and 4). This volcano is located to the east of a semicircular escarpment, the Bordiera escarpment, open to the east and rising, in places, up to 1000 m above the floor of the “caldera” it encloses. The escarpment has been interpreted as the scar of an ancient landslide, the Monte Amarelo landslide [Day *et al.*, 1999]. A minimum age of 80 ka has been suggested for the landslide, but this age estimate is poorly constrained [Fonseca *et al.*, 2003]. Since that time, volcanic activity has been almost entirely contained within the landslide scar,





**Figure 4.** (a) Oblique 3-D image of Fogo and Brava, viewed from the southeast, based on swath bathymetry offshore and SRTM data onshore. The relationship between the interpreted landslide scar on the island and the landslide debris offshore is clearly seen. (b) Plan (map) view of Fogo and the surrounding seafloor showing the relative extent of the landslide scar and debris field and the position of the Pico do Fogo volcano within the landslide scar. Contours are at 200 m intervals with thousand meter contours in bold (orange, 1000 m; green, 2000 m; blue, 3000 m). The volcanic cones on the right of the image are on the lower slope of Santiago island. For location, see Figure 3.

giving rise to the present-day Pico do Fogo volcano. Prior to 1785, frequent eruptions from the summit of the volcano were recorded; since that time, eruptions have occurred from fissures near its base [Fonseca *et al.*, 2003]. It has been suggested that a similar change in behavior occurred prior to the Monte Amarelo landslide and that it is a sign of flank instability [Day *et al.*, 1999].

[7] The small island of Brava has not been volcanically active in historical time, although it exhibits higher levels of seismicity than Fogo [Fonseca *et al.*, 2003]. Santiago is relatively old and deeply eroded. Volcanic rocks give ages of 6–0.3 Ma, but uplifted ocean floor of Jurassic age is also exposed on the island [Holm *et al.*, 2006].

**Table 1.** Landslide Parameters<sup>a</sup>

Island	Landslide	Deposit Area (km <sup>2</sup> )	Volume (km <sup>3</sup> )	Runout (km)	Slope <sup>b</sup>	Age
Fogo	Monte Amarelo	650	130–160	45	25–3°	>80 ka
Santo Antao	Tope de Coroa 2	540	50? <sup>c</sup>	40	13–6°	200–400 ka
Santo Antao	Tope de Coroa 1	1460	150? <sup>c</sup>	50	13–3.5°	>500 ka
Santo Antao	North-northeast	>340	?	>30	14–2.7°	0.7–1.4 Ma?
Santo Antao	Northeast	>450	?	>35	10–4°	0.7–1.4 Ma?
Sao Vicente	Southwest	820	80? <sup>c</sup>	40	9.5–3°	4–6 Ma?
Sao Nicolau	North	>860 <sup>d</sup>	?	>25	16–2.7°	>5.8 Ma?
Sao Nicolau	Southeast	970?	?	45?	25–1.7°	>5.8 Ma?

<sup>a</sup>Note that the “landslide” on the north side of San Nicolau is probably made up of at least three events. Postlandslide processes, such as volcanic activity, sedimentation, or erosion by canyons, may have modified slopes.

<sup>b</sup>Slope gradients have been measured only for submarine slopes where multibeam bathymetry is available.

<sup>c</sup>Assumes 100 m average thickness.

<sup>d</sup>Includes more than one landslide event.

[8] The multibeam data east of Fogo show a smooth, steep (25°, Table 1) upper slope and an area of irregular blocky topography on the lower slope. The area of blocky topography is elevated by 100–400 m relative to areas to the north and south (Figures 3 and 4). This contrasts with the more regular mounded topography of the western slope of Santiago to the east and the northern and western flanks of Fogo itself. Mounds are largely absent from the southern flank of Fogo, which appears to be sediment covered and characterized by thin sediment failures. By analogy with other volcanic islands, e.g., Canary Islands [Masson, 1996; Masson *et al.*, 2002], the area of irregular blocky topography is interpreted as a debris avalanche deposit, confirming that the Monte Amarelo scarp onshore is indeed a landslide headwall. The steep upper slope results from infilling of the landslide scar by postlandslide volcanic activity. The positive topographic anomaly of 100–400 m associated with the avalanche deposit suggests a volume in excess of 100 km<sup>3</sup> (Table 1). The more regular mound-like features are also seen around other volcanic islands [e.g., Gee *et al.*, 2001b], where they are interpreted as volcanic cones. The slopes of the small island of Brava, in the extreme southwest, are relatively smooth with only a few volcanic cones visible (Figure 4). Volcanic cones are more abundant in the depression between Brava and Fogo. No evidence of landsliding is seen on Brava.

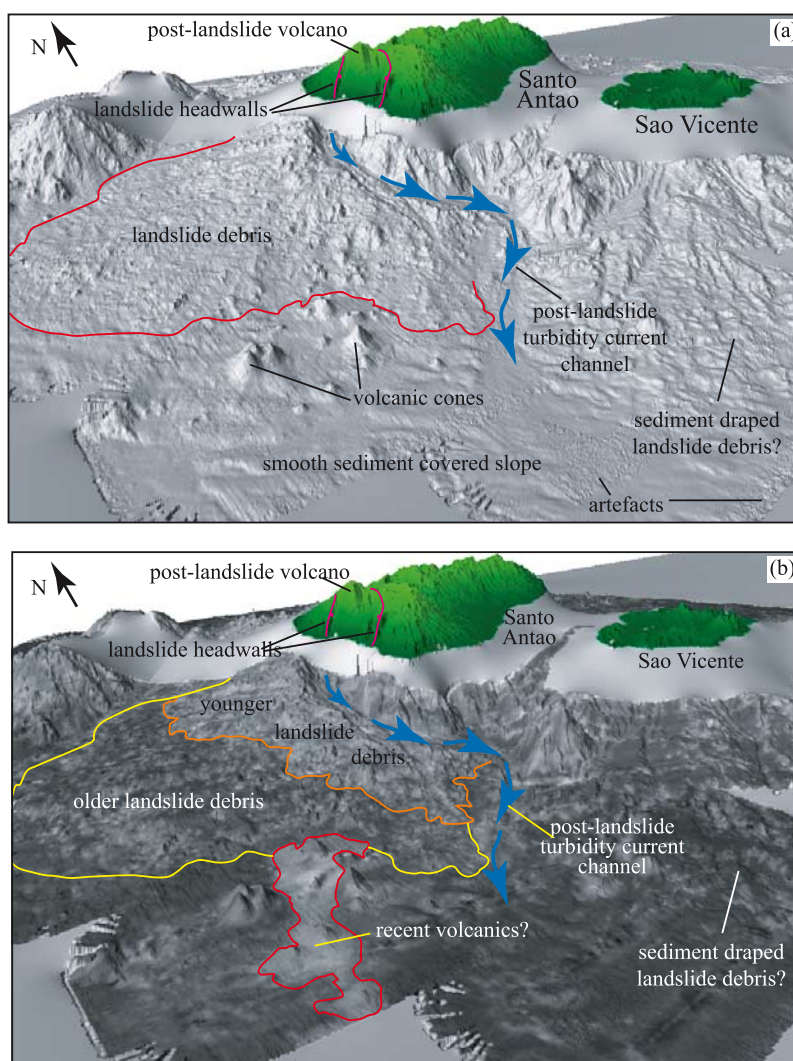
## 4.2. Santo Antao

[9] The southern half of the island of Santo Antao is dominated by the Tope de Coroa volcanic peak. Volcanic rocks erupted from this volcano are among the youngest on the island, with an age of

around 170 ka [Holm *et al.*, 2006; Plesner *et al.*, 2002]. The Tope de Coroa volcano lies within a horseshoe-shaped escarpment opening to the southwest, which we interpret as a landslide scar (Figure 2c). Part of possible second landslide scar, seen on land to the east of the more obvious horseshoe-shaped feature described above, but also offsetting the coast and expressed in the submarine bathymetry, may represent the remnants of a second, older landslide feature (Figure 2c).

[10] Multibeam images show an area of blocky terrain and overall positive relief, interpreted as a debris avalanche deposit, on the southern flank of the island. This deposit is cut by a deep submarine canyon originating on the island slope immediately seaward of the Tope de Coroa volcano (Figure 5). The blocky terrain contrasts strongly with the smooth sediment-covered seafloor that occurs farther downslope. A group of large volcanic cones, some up to 2 km across, interrupt this smooth seafloor. Backscatter images of the southern flank of Santo Antao reveal further details of the slope morphology (Figure 5). In particular, two areas of distinctly different backscatter characterize the area of blocky terrain on the southern island flank. These are interpreted as evidence for two debris avalanches of different ages, with the younger avalanche deposit (Tope de Coroa 2; Table 1) having higher backscatter because it is covered by a thinner sediment drape than the older avalanche deposit (Tope de Coroa 1; Table 1). The backscatter map also shows a north–south elongated patch of exceptionally high backscatter in the center of the group of volcanic cones on the lower slope (Figure 5). This is interpreted as a lava flow field with little or no sediment cover; it clearly postdates the older debris avalanche deposit. Back-





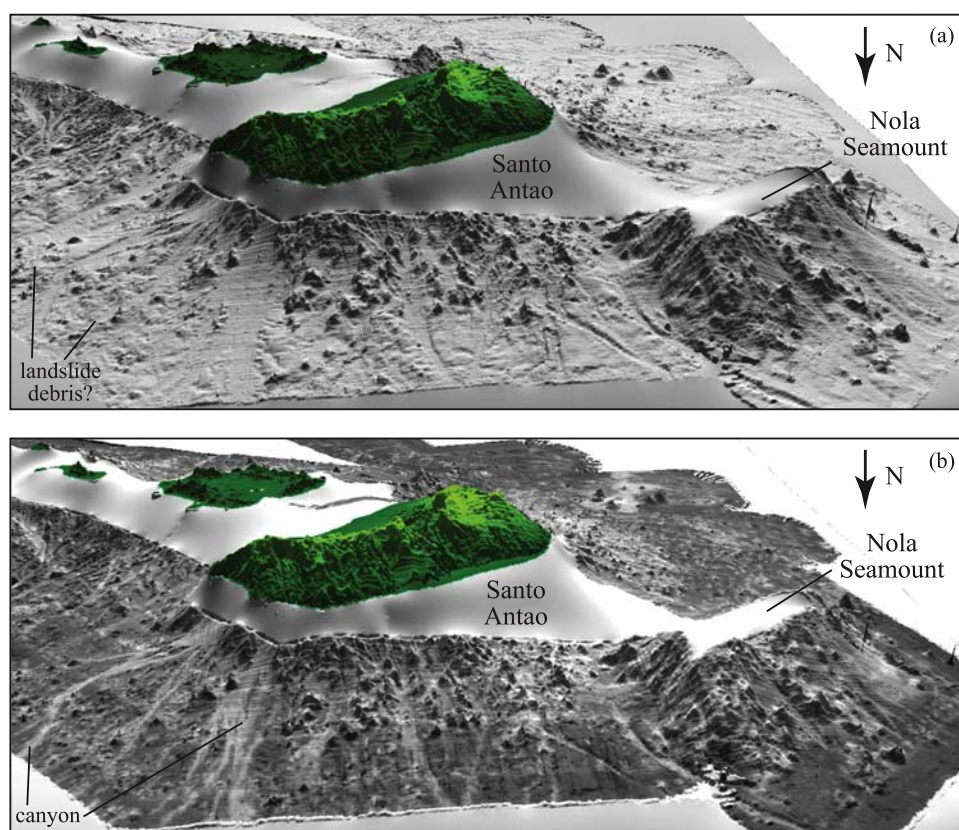
**Figure 5.** (a) Oblique 3-D image of Santo Antao and Sao Vicente, viewed from the south-southwest, based on swath bathymetry offshore and SRTM data onshore. The most recent landslide scar, surrounding the Tope de Coroa volcano, can be seen on Santo Antao. The large mound of landslide debris southwest of Santo Antao is cut by a more recent turbidity current channel or canyon. A less pronounced area of rough topography southwest of Sao Vicente may represent an older debris deposit partially smoothed by later sedimentation. (b) Same view as Figure 5a, but with multibeam backscatter draped over the 3-D topography. Backscatter variations suggest that the debris mound off Santo Antao has been built by at least two landslides, with the lower backscatter (darker) of the older part of the deposit due to greater postemplacement sediment cover. The extremely high backscatter patch surrounding some of the volcanic cones on the lower slope is interpreted as an area of volcanic material that postdates at least the older debris field. For location, see Figure 3.

scatter anomalies are absent from the area around the mouth of the turbidity current channel on the smooth lower slope. This again suggests a drape of pelagic sediment overlying this system, with little recent turbidity current activity.

[11] The northern part of the island of Santo Antao is composed of relatively old (0.3–1.4 Ma) volcanic rocks [Holm *et al.*, 2006]. The shape of the coastline is suggestive of landslide scars opening to both the northeast and north-northeast, but the

deeply eroded terrain casts doubt on the recognition of landslide headwalls onshore (Figures 6–8). Bathymetric and backscatter data from the island slopes show a contrast between the northeastern and northern flanks (Figure 6). On the northeast flank, the upper slope consists of sections of relatively low gradient smooth seafloor (maximum 10–14°), interspersed with rougher, steeper sections (up to 22°). By analogy with the Canary Islands [Gee *et al.*, 2001a; Watts and Masson, 1995] we interpret the rougher, steeper sections



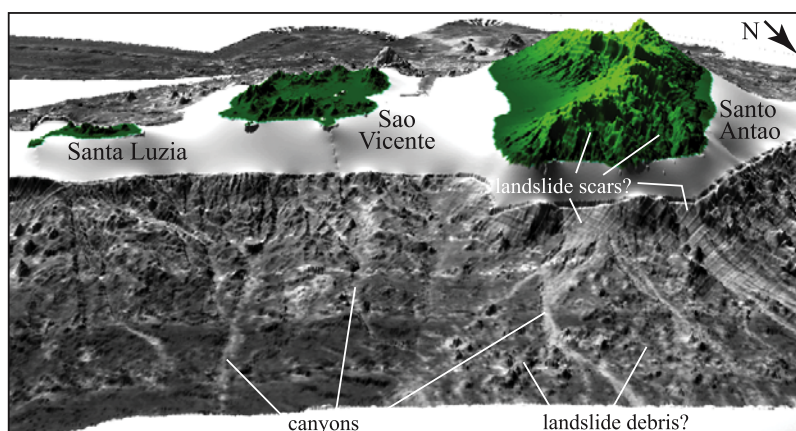


**Figure 6.** (a) Oblique 3-D image of Santo Antao and Nola Seamount, viewed from the north, based on swath bathymetry offshore and SRTM data onshore. The image shows areas of rough, steep upper slope, interpreted as areas of constructional volcanic slope, to the northwest of the island and seamount. Northeast of the island, areas of rough, steep upper slope are interspersed with areas of smooth, lower gradient slope. The latter are interpreted as ancient, sedimented landslide scars. A possible field of landslide debris is seen on the lower slope in this region. (b) Same view as Figure 6a, but with multibeam backscatter draped over the 3-D topography. The more active canyons are picked out as ribbons of high backscatter (lighter). Canyons are particularly well developed within landslide scars. For location, see Figure 3.

as constructional volcanic slopes, and the smoother, gentler sections as areas affected by landsliding. The lower slope is characterized by a relatively small-scale roughness (when compared to rough sections of upper slope) that appears smoothed, at least in part, by sediment cover. By comparison with the southern flank of the island, this lower slope area is interpreted as an area of sediment-draped landslide deposits. The backscatter map shows areas with distinctly different backscatter character within the smooth, sediment-covered seafloor. Elongate, high-backscatter features, oriented downslope, are interpreted as shallow canyons or channels; the high-backscatter suggests that these are active features transporting coarse sediment from the island. Low backscatter characterizes the areas between the channels, suggesting fine-grained sediments, either pelagic drape or

fine-grained channel overbank deposits, draping areas of stable slope.

[12] In contrast to the variable character of the upper slope of the northeast island flank, the upper slope of the northern flank, which merges with the flank of Nola Seamount to the west, is uniformly rough and steep (Figure 6). A relatively sharp change in character of the slope, at approximately 2200 m water depth separates the relatively steep upper slope (up to  $16^\circ$ ) from a gentler, smoother lower slope (typically  $<7^\circ$ ), although the slope break is gradual rather than abrupt. Canyons cutting this slope are less well defined by their backscatter than those on the northeast flank, suggesting less frequent activity. Overall, the backscatter signal of the slope is lower than the area north of the island that is characterized by landslide



**Figure 7.** Oblique 3-D image of Santa Antao and Sao Vicente, viewed from the northeast, based on swath bathymetry offshore and SRTM data onshore and with multibeam backscatter superimposed. Areas of smooth, relatively low-gradient, upper slope northeast of Santo Antao are interpreted as landslide scars. These correspond to possible deeply eroded landslide scars on the island. Canyons have preferentially formed in the landslide scars offshore. Probable landslide deposits can be identified on the lower slope. In contrast, there is no evidence for landsliding north of Sao Vicente. Here, the upper slope is uniformly steep and cut by small canyons, although these canyons do not generally exhibit high backscatter and are probably largely inactive. The lower slope is characterized by smooth, low backscatter (dark), suggesting a thick sediment drape. For location, see Figure 3.

deposits. Thus evidence for landslide scars and/or deposits is lacking on the northern island flank.

### 4.3. Nola Seamount

[13] Nola Seamount lies immediately to the west of Santo Antao (Figure 1). It is elongated northeast–southwest, with two distinct summits separated by a central saddle (Figures 8 and 9); at their shallowest points these both rise to within <100 m of the sea surface. Bathymetry maps show relatively steep (typically >20° on the upper slope), rough slopes facing north, northeast and southwest, and a gentler (15°), smoother slope facing northwest, particularly west of the saddle between the twin peaks (S on Figure 9). Backscatter maps generally reflect the pattern of rough (rock outcrop) and smooth (sedimented) seafloor, except for the area of smooth seafloor west of the central saddle that shows unexpected (and unexplained) high backscatter (Figure 9). There is no evidence of landslide deposits (such as the speckled backscatter pattern seen south of Santo Antao) on the flanks of the seamount.

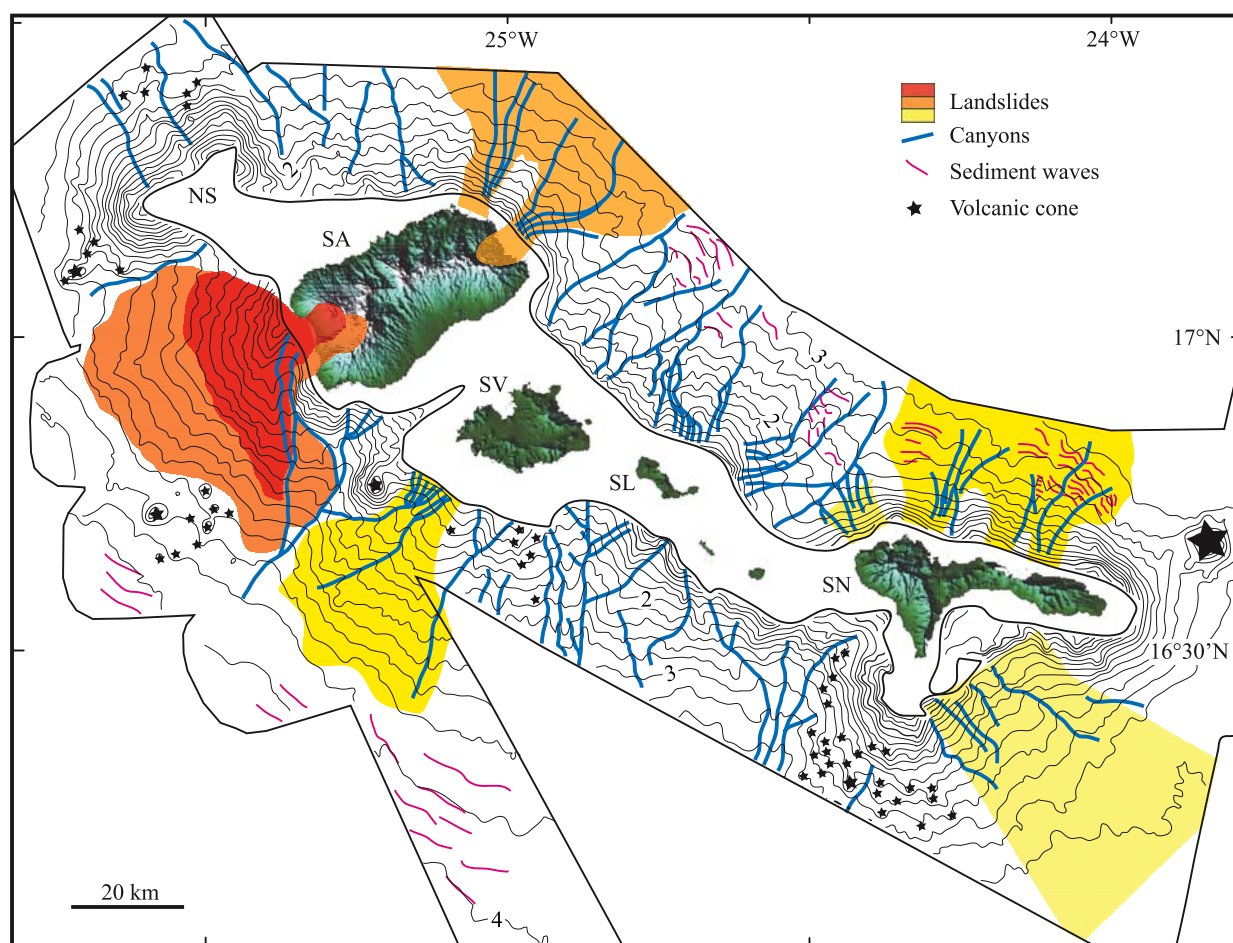
### 4.4. Sao Vicente

[14] Sao Vicente island appears to be relatively old and deeply eroded. Volcanic activity has been dated between 7.5 and 0.3 Ma [Holm *et al.*, 2006], but most of the island is covered with so-called “oldest” and “intermediate” volcanic

sequences erupted between 4 and 6 Ma [Jorgensen and Holm, 2002]. To the north of Sao Vicente (and the smaller island of Santa Luzia immediately to the east) the upper submarine slope is relatively steep and cut by many small canyons (Figure 7). These canyons have a dendritic morphology and merge downslope into a small number of shallow features crossing the relatively gentle lower slope. The canyons have a weak signature on backscatter maps (e.g., compared to canyons north of Santo Antao, Figure 7) suggesting little sediment transport during recent times. Backscatter levels are generally low on this entire slope, suggesting background hemipelagic sedimentation, and there is a clear backscatter contrast between the slope north of Sao Vicente (lower backscatter) and that northeast of Santa Antao (higher). There is no evidence of landslide deposits on the smooth lower slope.

[15] The southern slope of Sao Vicente is characterized by a steep, rough slope in the east and west separated by a smoother, gentler slope in the center. A bulge in the bathymetric contours (Figure 8) and a speckled character in backscatter maps on the lower slope (Figure 5) suggest an area of landslide deposits (Figure 8). These landslide deposits have a smoother character than the deposits south of Santa Antao immediately to the west and are dissected by canyons, suggesting a relatively old feature.





**Figure 8.** Interpretation of the offshore geomorphology of the northwestern Cape Verde Islands. Contours are at 200 m intervals. Colors indicate relative ages of debris avalanche deposits from red (youngest) to pale yellow (oldest). Boundaries of younger deposits are generally better constrained than those of older deposits. Sediment waves, usually parallel to contours, are interpreted as turbidity current waves. Note that canyons often preferentially develop within landslide scars (see text for discussion). NS, Nola Seamount; SA, Santo Antao; SV, Sao Vicente; SL, Santa Luzia; SN, Sao Nicolau.

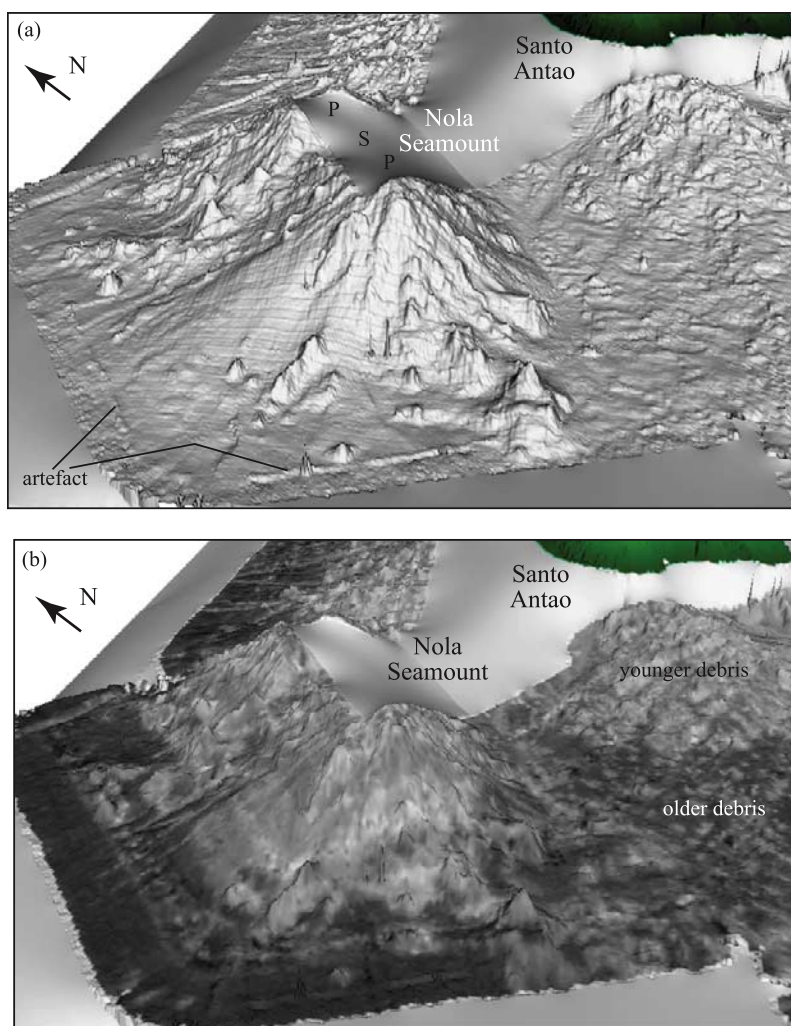
#### 4.5. Sao Nicolau

[16] Sao Nicolau is old and deeply eroded; biostratigraphic constraints from limestones intercalated with the main lava sequences on Sao Nicolau indicate that the latter were erupted between 11.8 and 5.8 Ma (possibly between 6.2 and 5.8 Ma) [Bernoulli *et al.*, 2007]. The northern flank of the island is the most heavily sedimented of all the areas surveyed during this work. Nevertheless, the upper slope can be divided into regions of steep, rough topography and gentler, smooth topography (Figure 10). This is clearly shown on profiles drawn perpendicular to the bathymetric contours (Figure 11). Such profiles of volcanic island slopes has been shown to be a good indicator of whether or not the island flank has been affected by large-scale slope failure, even when later sedimentation or erosion

has modified the slope [Gee *et al.*, 2001a; Watts and Masson, 1995]. Slopes that have failed are relatively smooth and are characterized by a gradual decrease in slope gradient downslope (profiles 2, 3, 5, 6). Slopes that have not failed and have been created entirely by volcanic construction are rougher and have a steep upper slope, but the slope gradient decreases more rapidly downslope than that of failed slopes, giving an overall more concave profile (profiles 1, 4, 7). The former is the case for profiles 2, 3, 5 and 6 in Figure 11, the latter for profiles 1, 4 and 7, strongly suggesting their interpretation as profiles crossing areas affected by landsliding and constructional volcanic slopes, respectively (Figure 8).

[17] The lower slope north of Sao Nicolau is marked by a series of slope-parallel, gently sinuous



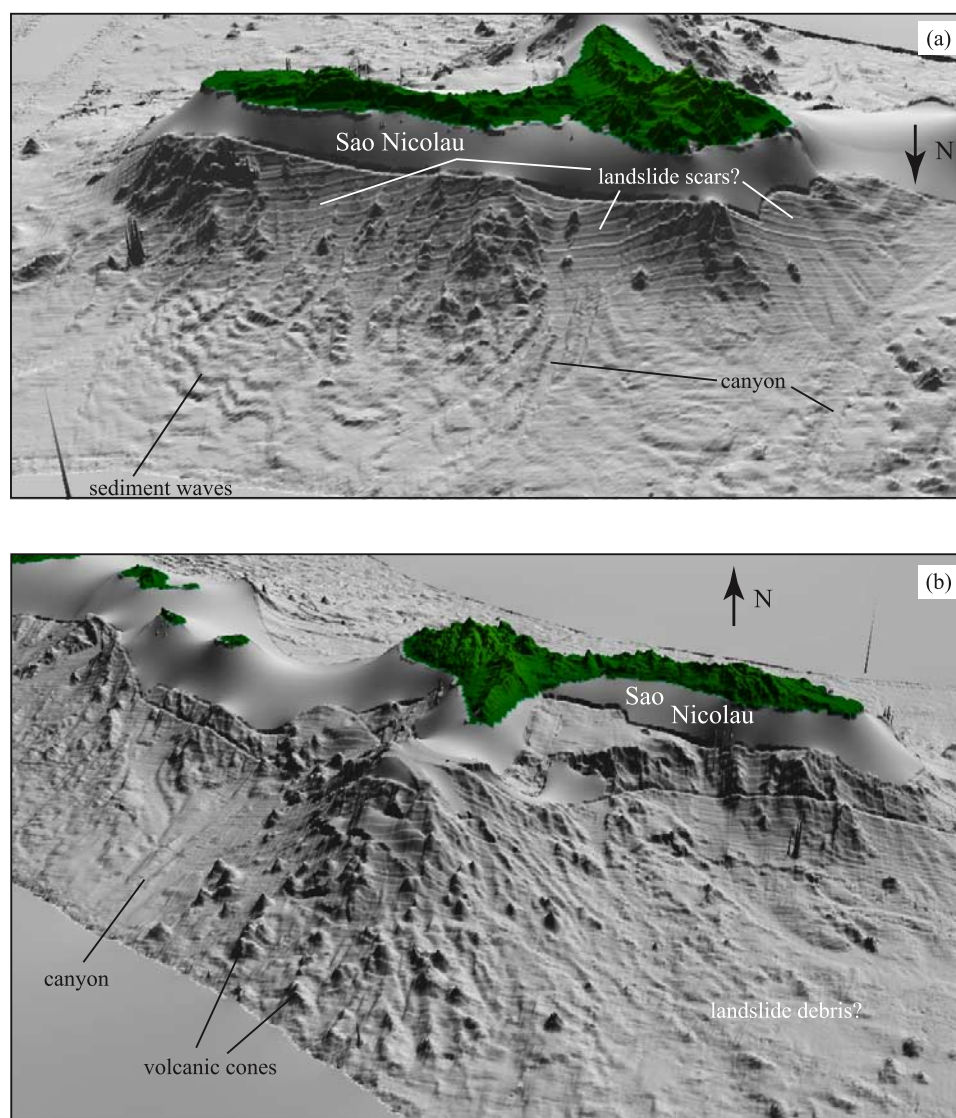


**Figure 9.** (a) Oblique 3-D image of Nola seamount, viewed from the west-southwest, based on swath bathymetry. The slopes of the seamount are characterized by large numbers of volcanic cones. Rough, steep upper slopes gradually change downslope to lower slopes that are largely smooth and sediment covered. The character of the seamount slopes contrasts sharply with that of the debris-covered slope southwest of Santo Antao. (b) Same view as Figure 9a, but with multibeam backscatter draped over the 3-D topography. In general, the distribution of high (light) and low (dark) backscatter follows the distribution of rough (volcanic) and smooth (sedimented) topography. For location, see Figure 3.

undulations. Taking into account the geometry of these features, and their association with several shallow slope canyons, they are interpreted as sediment waves built by turbidity currents [Wynn *et al.*, 2000], rather than indications of slope instability, such as slumping or creep folds. No evidence of landslide debris is seen on the lower slope, despite the probability that parts of the upper slope have been affected by landsliding.

[18] The southern flank of Sao Nicolau is the most enigmatic in terms of interpreting formative processes from slope morphology (Figure 10). A prominent submarine ridge that extends south from

the western end of the island is characterized by numerous volcanic cones and is clearly a volcanic construct. To the east of this ridge, a broad embayment in the island flank is marked by relatively gentle slope and an irregular seafloor that appears to contain elements of both of blocky and canyoned slopes. The lower slope is also marked by large irregular blocks that contrast with the regular volcanic cones on the adjacent ridge. This area is tentatively interpreted as being the site of a landslide, although both landslide scar and deposit appear to have been modified by subsequent sedimentation and erosion processes. A steeper section



**Figure 10.** (a) Oblique 3-D image of Sao Nicolau from the north based on swath bathymetry offshore and SRTM data onshore. Areas of smooth sedimented seafloor on the upper slope, interpreted as landslide scars, are interspersed with rougher, steeper areas, interpreted as constructional volcanic slopes (see Figure 11). Shallow canyons are preferentially developed in the landslide scars. Turbidity current sediment waves, probably associated with these canyons, are widely developed on the lower slope. (b) Oblique 3-D image of Sao Nicolau from the south. The prominent north–south submarine ridge south of the island shows a constructional volcanic morphology characterized by abundant volcanic cones. The area to the east of the ridge has probably experienced landsliding, but the extent of both scar(s) and deposit(s) are poorly constrained. For location, see Figure 3.

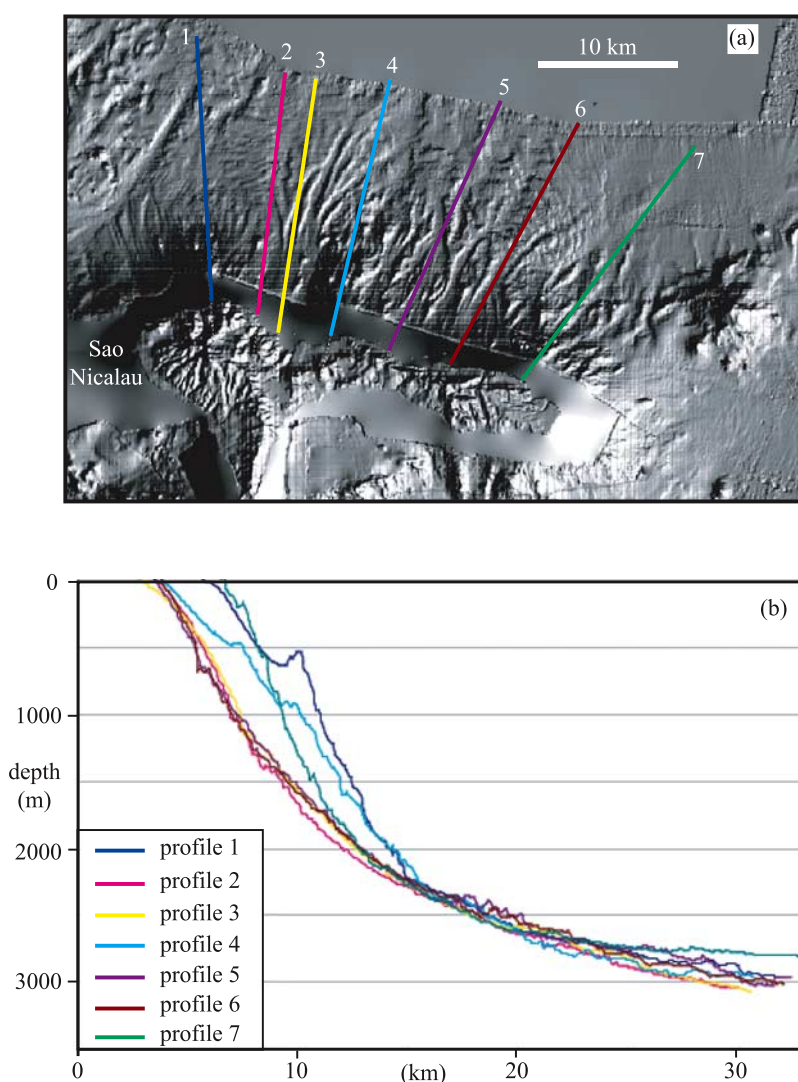
of slope at the eastern end of the southern flank is probably a constructional volcanic slope.

## 5. Discussion

### 5.1. History of Landslides in the Cape Verde Islands

[19] On the basis of morphological data, all the larger islands examined during our study, with the

exception of the eastern flank of Santiago, show some evidence of large-scale flank instability. Evidence for landslides is absent from the smaller island of Brava and from the flanks of Nola Seamount. The lack of any age information from the landslide deposits means, however, that any analysis of the history of large-scale landsliding in the Cape Verde Islands will contain a large measure of uncertainty.



**Figure 11.** Bathymetric profiles across the north slope of Sao Nicolau. (a) Profiles located on a plan view 3-D map of Sao Nicolau. For map location, see Figure 3. (b) Profiles illustrating differences between areas affected by landsliding (profiles 2, 3, 5, 6) and those of constructional origin (profiles 1, 4, 7). Profiles are stacked so that their parallel lower slope segments are coincident. This emphasizes the smoother character and gentler upper slope of the profiles through regions interpreted as landslide scars.

[20] The best-defined and probably most recent landslide is the Monte Amarelo landslide on the eastern flank of Fogo (Figure 4). The age of this feature is estimated as  $>80$  ka [Fonseca *et al.*, 2003]. However, this is not well constrained since it is based only on the occurrence of a marine abrasion platform covered by alluvium and aeolian sands which are believed to have been deposited at a time of pre-Holocene high sea level [Day *et al.*, 2005]. There is no evidence in the subaerial morphology or offshore bathymetry for other landslide sites on Fogo, or for earlier episodes of landslide from the same location of the Monte Amarelo landslide.

[21] The youngest landslide scar at the southwestern end of Santo Antao must be at least 200 ka in age, despite its fresh appearance, since the Tope de Coroa volcanic complex (0.17–0.2 Ma [Holm *et al.*, 2006]) is entirely contained within the scar. The southeastern part of the scar is floored by the Proto Coroa sequence (0.2–0.4 Ma [Holm *et al.*, 2006]), which might even suggest that the landslide scar is older than 0.4 Ma. However, the southeastern wall of the scar truncates the Younger Tarrafal sequence (also dated at 0.2–0.4 Ma [Holm *et al.*, 2006]). Thus the likely landslide age is between 0.2 and 0.4 Ma. The older landslide scar at the southwestern end of Santo Antao is filled with volcanic rocks



of the Younger Tarrafal and Monte Frado sequences. The latter dates from 0.4 to 0.5 Ma [Holm *et al.*, 2006], indicating that the landslide must be >0.5 Ma in age. Landslides at the northeast of the island cannot be dated from the available data, but much of this part of the island is covered by volcanics dated at 0.7–1.4 Ma; this is also the likely age range for the landslides.

[22] The main periods of extrusive volcanism on the other major islands in the northern chain, Sao Vicente and Sao Nicolau, occurred at 4–6 Ma and >5.8 Ma, respectively [Holm *et al.*, 2006]. Morphological evidence for landslide scars and deposits can be identified offshore, but they have been extensively modified by later canyon cutting and sedimentation processes. Information that would place better constraints on the ages of these features is lacking.

## 5.2. Canyons and Landslide Scars

[23] Canyons are common features on the slopes of the northern island chain (Figures 6–8 and 10). In several places, groups of canyons originate within the submarine parts of landslide scars on the upper slope (e.g., north of Santo Antao and Sao Nicolau; south of Sao Vicente). This may be because landslide scars form topographic depressions that provide pathways through which later sediment transport is channeled. It may also reflect a concentration of postlandslide volcanism within landslide scars, such as on Fogo and Santo Antao, leading to enhanced production of volcanoclastic sediments in these areas. Concentrations of canyons on the upper slope may thus be an additional feature that can be used to identify old landslides, even when the morphology of the slope has been modified to an extent where even slope profiles cannot be used for this purpose. In the northern Cape Verde island chain, landslide areas north of Santa Luzia and southeast of Sao Vicente might be identified in this way (Figure 8).

## 5.3. Tsunami Hazard

[24] The magnitude and propagation characteristics of tsunamis resulting from landslides on oceanic islands have been much debated [Mader, 2001; Masson *et al.*, 2006; McMurtry *et al.*, 2004; Moore and Moore, 1984; Ward and Day, 2001]. Despite this controversy, it is generally agreed that tsunamis generated in this way are likely to be among the largest such events to affect ocean basins. For example, tsunami runup in excess of 300 m on the Hawaiian Islands [McMurtry *et al.*,

2004; Moore and Moore, 1984] and perhaps 150 m on Gran Canaria in the Canary Islands [Perez-Torrado *et al.*, 2006] has been proposed.

[25] In the Cape Verde Islands, only Fogo and the southwest flank of Santo Antao can be considered to pose a tsunami threat at the present day. However, the Tope de Coroa volcano on the southern flank of Santo Antao has been inactive for the past 170 ka [Holm *et al.*, 2006] and unless the volcano is reactivated, its stability would not appear to be in question. Pico do Fogo on the island of Fogo, on the other hand, is among the most active volcanoes on earth, and north–south oriented fissures and faults that have formed during eruptions since the 18th century have been interpreted as evidence for the onset of a new phase of flank instability [Day *et al.*, 1999]. The constructional volcanic slopes of up to 25° on the eastern submarine flank of Fogo are also among the steepest seen anywhere in the Cape Verdes. It seems highly probable that a future east directed landslide on Fogo will occur, although the timing of such a landslide is entirely unpredictable. Remnants of the previous failure (the Bordiera scarp, Figure 2) could be extrapolated to suggest that the previous Monte Amarelo volcano was considerably larger than today's Pico do Fogo volcano prior to the former's collapse. This might suggest that the next landslide is some time away. However, the failure plane for the Monte Amarelo landslide, on which the Pico do Fogo is built, might form a plane of weakness that will facilitate future landslides, as has been suggested for Tenerife in the Canary Islands [Masson *et al.*, 2002].

[26] Any future collapse of Pico do Fogo would generate a tsunami that could have catastrophic effects on the nearby island of Santiago. The capital city of the Cape Verde Islands, Praia, with a population of over 100,000, is located on the southern tip of the island, only about 80 km from Fogo. This is similar to the distance between Tenerife and Gran Canaria in the Canary Islands; a landslide on Tenerife is believed to have generated a tsunami with runup of about 150 m on Gran Canaria about 0.85 Ma [Perez-Torrado *et al.*, 2006]. Furthermore, the densely populated West African coast, including the city of Dakar with a population of about 2.5 million, lies only about 750 km farther east.

## 6. Conclusions

[27] Large-scale landslides have affected all of the larger islands in the Cape Verde group examined

during this study, at some point in their geological evolution. The small island of Brava and the Nola seamount at the northwestern extremity of the island group do not appear to have experienced landsliding. Sao Nicolau and Sao Vicente, in the northern island chain, are old and deeply eroded and, although both show evidence for landsliding in the distant past, pose no geohazard threat at the present day. The most recent landslides have affected the eastern flank of Fogo (at about 80 ka) and the southwest flank of Santo Antao (0.2–0.4 Ma). On both islands, postlandslide volcanoes have been rebuilt inside the youngest landslide scar. Tope de Coroa volcano on Santo Antao has been inactive for the past 170 ka and a new landslide appears unlikely unless volcanic activity resumes. However, Pico do Fogo volcano on Fogo Island is an extremely active volcano, and possible signs of renewed flank instability have been observed during recent eruptions. Failure of the eastern flank of Fogo would pose a serious tsunami threat to the adjacent island of Santiago, and possibly to the West African coast some 750 km distant.

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