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# Offshore evidence for a huge landslide of the northern flank of Tahiti-Nui (French Polynesia)

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[1] A bathymetric analysis of the flanks of Tahiti-Nui (French Polynesia) reveals the existence of a major catastrophic north-directed landslide during its eruptive history. The related debris-avalanche (DA) deposits extend north 70 km from the island shore and have a total volume of about 800 km<sup>3</sup>. Two contrasted facies of the debris are recognized: (1) relatively small-sized material, including a few blocks with well-developed flow structures (elongate downslope-directed ridges and transversal pressure ridges), and (2) a scattering of large kilometer-sized individual blocks that form, in part, a prominent bathymetric hummock in the proximal central part of the landslide deposits. Bathymetric analyses suggest that the Tahitian failure evolved through two main successive shots. The DA debris were rapidly overlain by subsequent volcanic material, producing a smooth surface down to 1500 m below sea level. The on-land and offshore structures indicate a listric fault geometry for the landslide scar. The volume removed by the landslide is thus estimated between 400 km<sup>3</sup> and 450 km<sup>3</sup>. Discrepancy in the volume of the scar, and the debris derived from it, is due in part to expansion of the debris, to fragmentation of the avalanche, and to incorporation of sediments. Comparison with a recently recognized southern Tahitian landslide (Clouard et al., 2001) and with landslides recognized around the Hawaiian Islands and the Canary Islands shows that the huge northern Tahitian landslide described here has a reduced mobility in its central part. Perhaps the older Tetiaroa eruptive complex to the north acted as a buttress to inhibit movement of the DA products. The northern and southern Tahiti-Nui landslides moved in opposite directions away from the main central E-W directed rift zone that served as the main magma feeding structure. Then, the huge northern landslide strongly controlled the later volcano-structural evolution by capturing subsequent volcanic activity to the north, despite the northwestward displacement of the Pacific plate over the Society hot spot.

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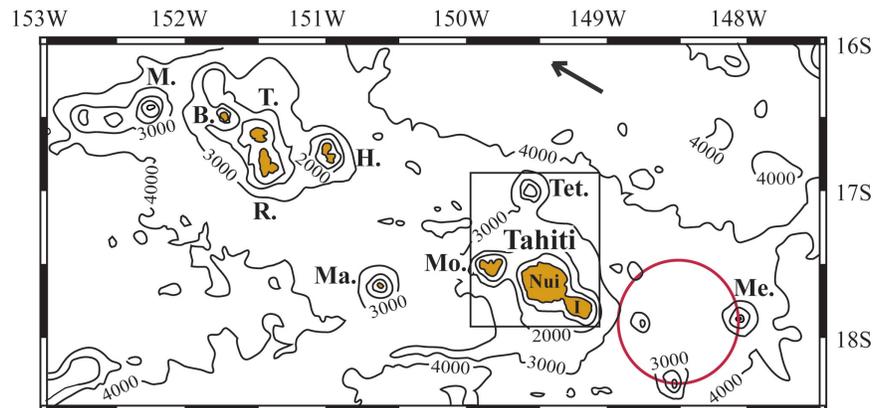
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## 1. Introduction

[2] Many volcanic edifices in intra-oceanic plate settings experience catastrophic landslide events

during their eruptive history. The Hawaiian Ridge in the Pacific [e.g., Lipman et al., 1988; Moore et al., 1989; Smith et al., 1999], the Canary Islands in the Atlantic [Holcomb and Searle, 1991; Watts and Masson, 1995; Gee et al., 2001; Krastel et al.,



**Figure 1.** Location of Tahiti at the southeastern end of the Society volcanic chain. The bathymetry is given in meters below sea level. The red circle indicates the current hot spot zone. The arrow shows the direction of Pacific motion. The rectangle delimits the area of Figure 2. M., Maupiti; B., Bora-Bora; T., Tahaa; R., Raiatea; H., Huahine; Ma., Maiao; Mo., Moorea; Me., Mehetia; Nui, Tahiti-Nui, I, Tahiti-Iti; Tet., Tetiaroa.

2001; Mitchell *et al.*, 2002; Hildenbrand *et al.*, 2003], and Reunion Island in the Indian Ocean [Duffield *et al.*, 1982; Gillot *et al.*, 1994; Ollier *et al.*, 1998] are typical examples. In most cases, those wasting-stages seem favored by dyke intrusions along rift zones [Walker, 1988; Elsworth and Voight, 1995], but gravitational spreading of the volcanoes [Van Wyk de Vries and Francis, 1997; Callot *et al.*, 2000], large regional earthquakes [Hampton *et al.*, 1996], as well as reactivation of basement faults underneath the edifices [Vidal and Merle, 2000] may influence the development of such instabilities. Two main types of landslides are classically distinguished [Varnes, 1978; Walker, 1988; Moore *et al.*, 1989]: (1) rotational landslides along a deep decollement and (2) lateral landslides due to listric faults. The first one consists in a slow moving of a part of the island, also called slump [Moore *et al.*, 1989, Smith *et al.*, 1999]. The second is more brutal. It generates long-running debris-avalanches (DA) that mainly disperse on the submarine slopes of the concerned edifice. The associated products present a blocky appearance, forming “hummocky terranes” that spread on important areas, extending tens of kilometers away from the source zone [Moore *et al.*, 1989; Hampton *et al.*, 1996; Teide Group, 1997, Masson *et al.*, 2002; Mitchell, 2003]. DA deposits present a wide variety of facies, whether or not they include large blocks, coarse-debris, finer debris, and flow structures [Mitchell *et al.*, 2002]. On the southern submarine flank of Tahiti Island (French Polynesia), blocky debris avalanche deposits have recently been recognized [Clouard *et al.*, 2001]. A major catastrophic landslide has also been proposed for the northern part on the basis of on-land morpho-

logical and geological data [Gillot *et al.*, 1993; Hildenbrand *et al.*, 2004]. We identify here, from new bathymetric data, the products related to this huge northern landslide. Their facies and geometry are analyzed and an estimation of the landslide volume is presented both from high-resolution bathymetric data and from an on-land numerical geomorphic analysis. These data provide insight into the mechanisms of the landslide and the run-out of the debris.

## 2. Geological Framework

[3] Tahiti is located at the southeastern end of the Society archipelago (Figure 1), in agreement with the northwestward displacement of the Pacific plate over a fixed hot spot during the last million years [e.g., Duncan and McDougall, 1976; Brousse and Léotot, 1988; White and Duncan, 1996]. The current hot spot zone extends somewhat 50 km farther southeast, as indicated by volcano-seismic crises linked to the growth of several seamounts [Talandier and Okal, 1984]. Tahiti is made up by two coalescent eruptive systems, defining the main island of Tahiti-Nui and the subsidiary island of Tahiti-Iti, which are aligned in the N120 direction of plate motion.

[4] The geology of Tahiti-Nui was recently reviewed [Hildenbrand *et al.*, 2004]. The volcanic evolution is marked by the concentration of magma ascents through a main E-W rift zone [Gillot *et al.*, 1993], which was responsible for the lateral destabilization of the main shield northern slope, around 0.87 Ma. A huge northern depression was thus created (Animation 1). Clouard *et al.* [2001]

have also recently identified a southern landslide. Geological, geomorphological and geochronological data [Hildenbrand *et al.*, 2004] show that subsequent volcanic activity has then been immediately concentrated to the north, constructing a second shield within the U-shaped depression (Animation 1). The flows rapidly overflowed the depression, covering the slopes of the main shield, or filling existing valleys (Animation 1). Finally, the southern depression was extensively buried around 500 ka (Animation 1).

[5] Subsequently, the heavy rainfall tropical climate induced a deep erosion of the volcanic structure, and the widespread development of mudflow deposits presently exposed in all the major valleys of Tahiti [Deneufbourg, 1965; Boutault, 1985; Hildenbrand, 2002; Gillot *et al.*, 2004; Hildenbrand *et al.*, 2004]. The presence of such products in the Papenoo drainage system yielded some authors [Clément *et al.*, 2003] to propose the existence of a recent landslide in the late evolution of Tahiti, which would be responsible for the present morphology of the upper part of the valley. This hypothesis has been debated [Gillot *et al.*, 2004], showing that the present morphological surface cannot fossilize the structural scar of a destabilization process initiated at least 390 kyr ago, but, on the contrary, result from a recent ongoing erosion process. Ultimately, the present study will help to conclude between the two hypotheses, since the outlet of the Papenoo valley is located in the investigated area.

### 3. Bathymetric Characteristics of the Northern Flank of Tahiti-Nui

[6] The northern flank of Tahiti has been completely surveyed by a multibeam sounder on board the R/V L'Atalante during the ZEPOLYF1 cruise in December 1996 [ZEPOLYF, 1997]; The bathymetric data were added to a compilation of multibeam data acquired during several previous cruises around Tahiti [Jordahl *et al.*, 2004]. On land, the topography of the island was processed with a 120-m-resolution DEM of Tahiti, obtained by degradation of an initial grid at 20 m. These data are first presented on a shaded relief map (Figure 2) including 500-m-interval isobaths. On land, a simplified geological map of Tahiti-Nui [Hildenbrand *et al.*, 2004] is draped on the topography.

[7] In this figure, one can note the existence of a prominent scattered surface on the northern sub-

marine flank of the main island. This unit extends as far as 70 km from the Tahitian coast and covers a possible total area of 2950 km<sup>2</sup>, even if the northwest part is poorly constrained. It is partly composed of massive blocks, some of which have apparent sizes exceeding several cubic kilometers. The chaotic aspect suggests debris-avalanche (DA) type deposits, which, in the detail, show facies variations (see the next section). To the west, the deposits form a pronounced lobe partly buttressed on the eastern edge of a submarine relief, which may be composed by products linked to older mass-wasting stages in the geological evolution of Moorea Island.

[8] The geographical extension of Tahiti-Nui northern DA deposits is well enclosed between the on-land limits of the northern landslide depression (Figure 2). It moreover coincides with a zone of residual negative gravimetric anomalies [Clouard, 2000], indicating that the northern flank of Tahiti-Nui is partly composed by material with a lower density than basaltic lava flows.

[9] In the zone of the landslide area, a relatively smooth surface overlies the down-slope blocky DA deposits (Figures 2 and 3). This surface likely corresponds to the external submarine part of the second shield. It is almost absent in the central submarine part, where a hummock exists.

[10] Close to the northern island shore, the slope of the second shield is partly covered by fan-like sedimentary units located in the prolongation of the main river outlets, especially in the prolongation of the Papenoo river (Figures 2 and 3).

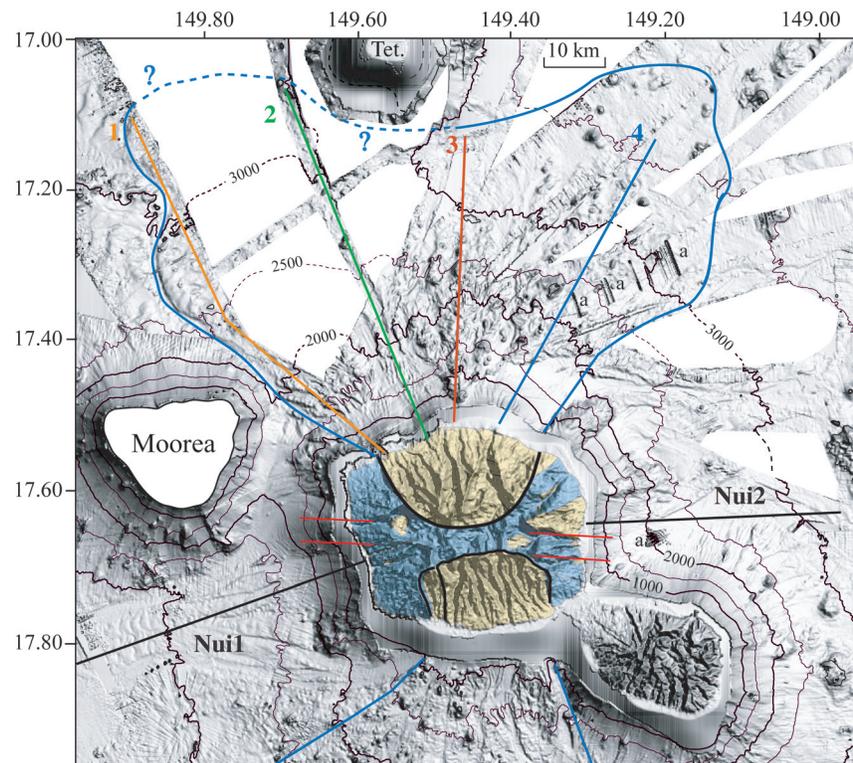
[11] Outside of the landslide area, submarine lava deltas are observed (Figures 2 and 3). They mainly prolong sectors of the island where thick lava flows capping the preserved flanks of the main shield have been observed on land [Hildenbrand *et al.*, 2004].

## 4. Geometry of the Landslide Deposits

[12] Despite the absence of seismic and acoustic data, which would help to better distinguish between geometrical and facies variations within the landslide deposits, the high-resolution bathymetric data here presented allow a fairly good estimation of their main characteristics (Figures 3 and 4).

### 4.1. Block Distribution and Flow Structures

[13] Tahiti northern landslide deposits show significant facies variations (Figure 3). Two main zones



**Figure 2.** Shaded relief map showing the hummocky aspect of Tahiti-Nui northern submarine slope. A geological map (Hildenbrand *et al.* [2004], simplified) is draped on the on-land topography, showing the main volcano-structural units: the main shield (in blue), the northern and southern landslide depressions (black lines), and the postlandslide second shield (in yellow). The axis of the main E-W rift zone is indicated by red lines. In the submarine part the blue solid line delimits the inferred area covered by the northern landslide deposits. The proximal extension of the southern landslide products is also shown [Clouard *et al.*, 2001]. Bathymetric curves are shown at 500 m intervals. Straight lines localize the bathymetric profiles exposed in Figure 5. Nonsurveyed zones are shown as white areas. Artifacts are indicated (a.). Tetiaroa old eruptive complex is located (Tet.).

are individualized, corresponding to (1) the central part of the DA and (2) the lateral parts of the DA:

[14] 1. The central part of the DA is characterized by an important concentration of large blocks distributed erratically on the submarine slope. A main density in the blocks is observed at a distance  $d$  comprised between 10 km and 35 km from Tahiti shore, but numerous large blocks are also exposed farther NE. In the distal part of the DA ( $d > 35$  km), the landslide products appear to

be dominantly composed of relatively small-sized debris, which include well-developed flow structures. Such structures typical look like pressure ridges described in the case of other landslide deposits, e.g., in the Canary Islands [Masson *et al.*, 2002] or on other planets [e.g., Head, 1996]. In the median part of the DA, dominant orientation of the ridges indicates a displacement of the landslide material mainly toward NE (Figure 3b). Note that, to the north and the northeast of Tahiti, flow structures appear to be overlaid and

**Figure 3.** (a) Gradient map enhancing the main characteristics of Tahiti northern submarine slope. Slope gradients are comprised between  $0^\circ$  (white) and  $35^\circ$  (black). The on-land geology and the submarine delimitation of the landslide deposits are drawn as in Figure 2. Black corners localize the geographical limits of Figure 4. P., outlet of the Papenoo valley. (b) Interpretative scheme highlighting the main characteristics observed on the northern submarine slope of Tahiti. In the area of the northern landslide, individual landslide blocks are shown in gray, longitudinal ridges are drawn in red, and axes of transversal pressure ridges are materialized by purple lines. The smooth surface overlying the landslide products is delimited by a yellow line. Sedimentary fans are represented with thin black lines. Outside the landslide area, lava deltas are drawn with thick yellow lines. P., outlet of the Papenoo valley.

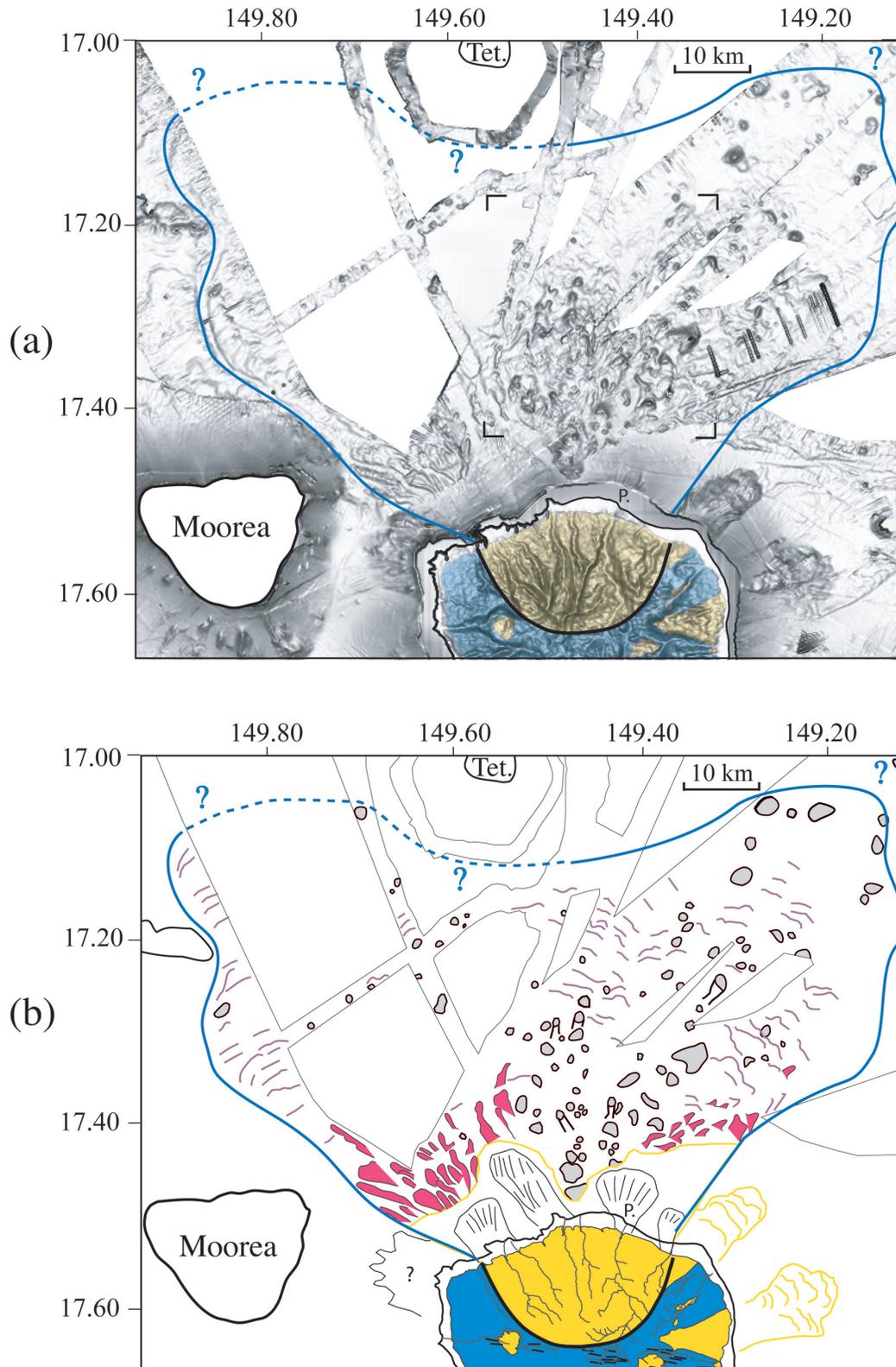
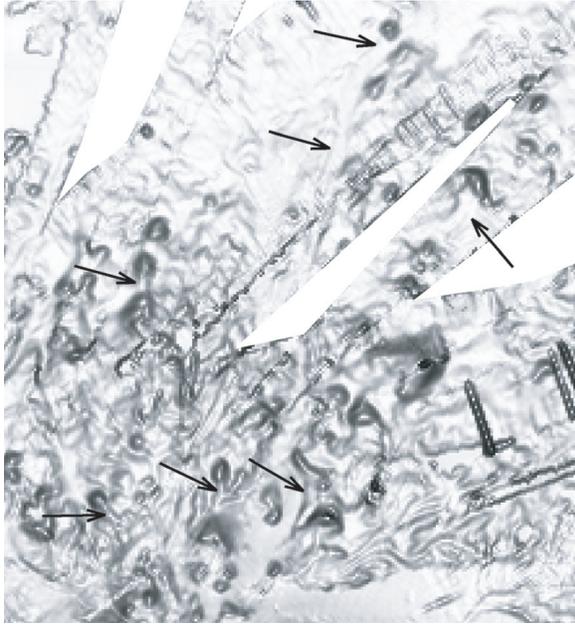


Figure 3



**Figure 4.** Detailed view of the central part of Tahiti northern DA deposits. Black arrows show submarine tracks fossilizing the late displacement of large blocks.

deformed by some of the large blocks, as revealed by the existence of tracks fossilizing block motion (Figure 4).

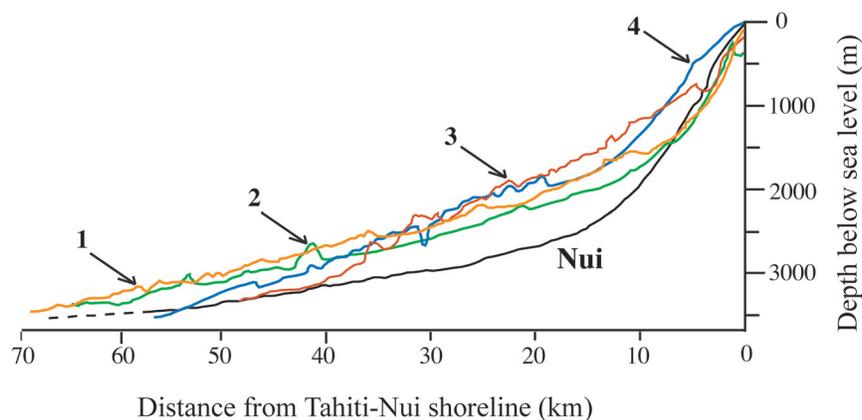
[15] 2. The lateral parts of the DA deposits do not show significant concentrations of large blocks (Figure 3). In contrast, these zones appear to be mainly composed of smaller-sized material including a few little blocks scattered randomly across the DA surface, up to distances of about 70 km from Tahiti shore. Two types of flow structures are visible in the debris, both to the east and to the

west. These are longitudinal downslope-elongated ridges in the proximal parts of the avalanche, and pressure ridges in the more distal parts. The morphology of the longitudinal ridges does not seem to result from recent erosion, since most of them are offset from the main submarine canyons. These peculiar structures may materialize the existence of shear stresses along the rims of the avalanche, as observed in the case of Icod landslide on Tenerife in the Canary Islands [Masson *et al.*, 2002]. Both longitudinal and pressure ridges here indicate a mean displacement of the DA products parallel to the lateral limits of the northern landslide.

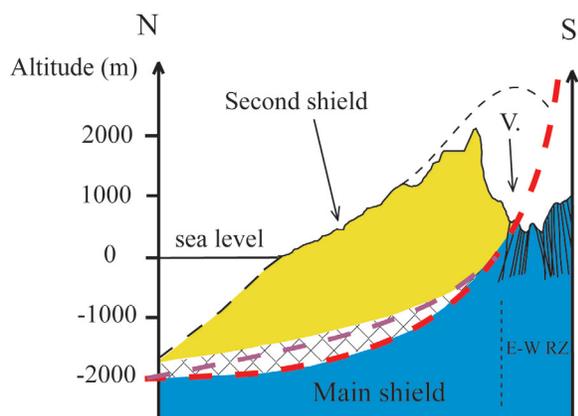
#### 4.2. Main Thickness and Volume of the Deposits

[16] Bathymetric cross sections have been constructed through the landslide deposits and across the island slope in zones not affected by the landslide (see Figure 2). The DA present systematic positive bathymetric anomalies (Figure 5), with a maximum of 1000 m at a distance comprised between 20 km and 30 km, which is similar to the products linked to the southern landslide [Clouard *et al.*, 2001].

[17] In the central part of the northern landslide area (Figures 2 and 5), profiles 3 and 4 have a speckled shape highlighting the important concentration of large blocks observed at the surface of the DA (Figure 3). Profile 3 has a convex upward shape, showing a high-slope bathymetric hummock, which rapidly vanishes to the north. Profile 4 shows, in addition, a prominent smooth surface close to the island shore, where it crosses sedimentary fans exposed in the prolongation of the



**Figure 5.** Bathymetric profiles across the northern landslide deposits (profiles 1, 2, 3, and 4) and outside the landslide area (“Nui” corresponding to a composite profile obtained from profiles Nui1 and Nui2). Vertical exaggeration of a factor 8.



**Figure 6.** Interpretative cross section through the northern part of Tahiti-Nui Island. The red and purple bold dashed lines indicate two inferred geometries for the northern landslide scar. The part of the DA buried by the postcollapse northern shield has an inferred thickness of 500 m. RZ, rift zone; V., Vaitamanu valley. Same vertical exaggeration as in Figure 5.

Papenoo river outlet. Profile 1 and profile 2 have lower slopes, and anomalies of about 200 m still remain as far as 70 km away from the Tahiti-Nui northern coral barrier (Figure 5).

[18] The “normal slope” (Figure 2, profiles Nui 1 and Nui 2, and composite profile Nui in Figure 5) has been used to generate a theoretical grid on the area of landslide deposits. It provides a realistic representation of the submarine slope of Tahiti-Nui before the northern landslide. The subtraction of this grid from the present measured surface then yields a good estimate for the volume of the DA deposits. Note that the un-surveyed zones (blacked in Figures 2 and 3) have not been taken into account. However, a rule of proportionality has been further applied to estimate the concerned missing volume, considering the area without data with respect to the total inferred area covered by the landslide products. A volume of 725 km<sup>3</sup> is thus computed for the DA deposits cropping on the northern flank of Tahiti-Nui.

[19] However, this volume does not take into account the part of the deposits subsequently buried by the construction of the postlandslide northern shield. A fraction of the DA may, indeed, have been preserved on land on the floor of the landslide depression, as observed in the case of large landslides on Reunion Island [Duffield *et al.*, 1982], La Palma Island and Tenerife Island [Navarro and Coello, 1989; Masson *et al.*, 2002]. On Tahiti, the volume of the inferred buried part is

not constrained precisely, but it can be maximized, taking into account a triangular geometry for the deposits, with a maximal thickness of 500 m (Figure 6). The additional volume here inferred does not exceed 100 km<sup>3</sup>. Thus the total volume of the DA is broadly estimated to be about 800 km<sup>3</sup>.

## 5. Estimation of the Volume Removed on Land From Geomorphic Analyses

### 5.1. Precollapse Geometry of the Main Shield

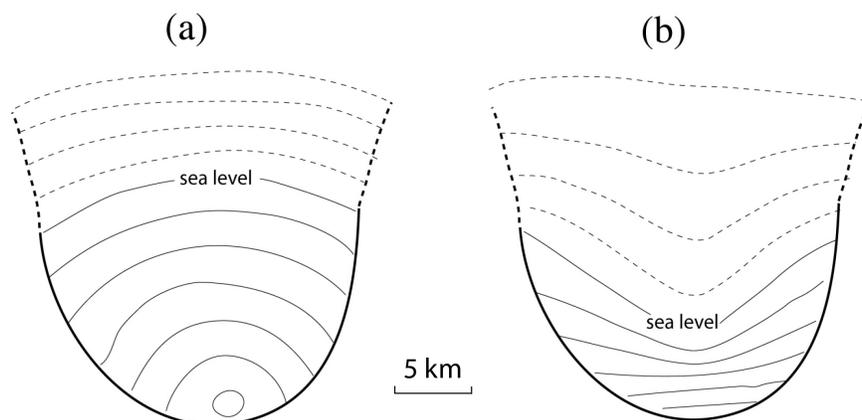
[20] Although overlain by later flows deposits, the original structural slopes of the main shield define four morphological surfaces preserved in the NW, NE, SW and SE sectors of Tahiti-Nui (Figures 2 and 3). Their slope prolongation intersects close to the present center of the island and defines a main conical eruptive center culminating at a mean elevation of 3250 m. Data interpolation for the missing part allows a fairly good reconstruction of the precollapse geometry. The subaerial volume then computed for the main shield is about 1000 km<sup>3</sup>.

### 5.2. Geometry of the Northern U-Shaped Depression

[21] The contact between the postlandslide second shield and the underlying DA is observed at a mean depth of 1500 m (Figures 2 and 3). This is thus a minimum depth for the roof of the landslide deposits. The mean thickness of the landslide deposits exposed in the proximal part of Tahiti northern slope is about 500 m. Therefore the basal scar of the landslide depression may be located at a maximal depth of about 2000 m at the latitude of Tahiti-Nui northern shore (Figure 6).

[22] The geological contact between the two nested shields is quite well established on land (Figures 2 and 3). In the center of Tahiti-Nui, it extends up to the southern bank of the Vaitamanu valley (Figure 6). The precise location of the former landslide headwall remains doubtful, since important erosion has further occurred. However, it may coincide with the southern end of the main E-W rift zone [Gillot *et al.*, 1993] (Figure 6).

[23] Between the main rift zone and Tahiti northern shoreline, the floor of the northern landslide depression is not directly exposed. The thick base of the second shield, however, crops in the deepest parts of the northern valleys, up to a distance of about 12 km from the shore [Hildenbrand *et*



**Figure 7.** Surfaces used for estimation of the volume removed by the landslide. Curve levels are drawn at 500 m intervals. Dashed lines for the submarine part. (a) Upper surface of the main shield inside the landslide area. (b) Lower surface inferred from the listric geometry of the purple landslide scar presented in Figure 6.

*al.*, 2004], providing constraints on the minimal depth of the landslide scar.

[24] The landslide profile can then be associated with a listric fault, which starts on land with a subvertical slope at the head of the landslide and has a gentle external slope  $\alpha$  close to Tahiti northern shore (Figure 6). Two extreme geometries can be inferred, corresponding respectively to  $\alpha$  values of  $0^\circ$  and  $10^\circ$  (Figure 6).

### 5.3. Estimation of the Volume Removed by the Landslide

[25] The rims of the depression have been first extracted from the surface of the prelandslide main shield. The two profiles from Figure 6 has then been used inside the area of the landslide depression. As for the estimation of the DA volume, each of them defines a lower theoretical surface, which, compared to the upper surface of the main shield (Figure 7), yields a broad estimation for the volume removed by the landslide. The two values obtained for  $\alpha$  values of  $10^\circ$  and  $0^\circ$  are of about  $400 \text{ km}^3$  and  $450 \text{ km}^3$ , respectively. This is significantly higher than the volume estimated at  $299 \text{ km}^3$  for the southern landslide [Clouard *et al.*, 2001].

## 6. Discussion

### 6.1. Landslide Mechanisms and DA Run-out

[26] Tahiti-Nui northern and southern landslides occurred in opposite directions, on both sides of the main E-W rift zone. They were thus likely generated by magma push along this main discon-

tinuity, which induced a dilatation of the edifice in the N-S direction. Constant earthquakes and tremor resulting from magma ascents along the rift zone may also have favored the destabilization of the island flanks. Gravitational spreading of the edifice, proposed as a driving mechanism of flank destabilization on other volcanic systems [e.g., Callot *et al.*, 2000], may not have been significant on Tahiti, since it requires the existence of thick sedimentary layers at the base of the volcano, which are not observed on the seafloor around Tahiti [Binard *et al.*, 1993]. The absence of significant weak layers such as pyroclastic deposits, palaeosols, or large hydrothermally altered bodies in the Tahiti main shield volcano-stratigraphy also rules out the possibility that the northern landslide could have been favored by slipping of volcano sectors on such low-cohesion levels [Hürlimann *et al.*, 1999].

[27] The total volume here estimated for Tahiti northern landslide deposits ( $800 \text{ km}^3$ ) is about two times higher than the estimated volume of materials removed on land ( $400\text{--}450 \text{ km}^3$ ). Two main hypotheses may be proposed to account for such a discrepancy:

[28] 1. The northern DA products would result from several landslide events. Old landslides might, indeed, have occurred during the early submarine stage of growth of Tahiti eruptive complex, possibly associated with the early individualization of the main E-W rift zone. Repeated destabilization of Tahiti northern flank during the aerial evolution of the island, is, however, not supported by geological data. The main shield, is, indeed, composed of a regular succession of vol-

canic flows dated between  $1.37 \pm 0.02$  Ma and  $0.87 \pm 0.02$  Ma [Hildenbrand *et al.*, 2004]. The oldest lava flows, are exposed in the deeper parts of the major valleys, while the youngest compose the external flanks of the island at the periphery of the volcanic structure, which is a consequence of the gentle external dip of the lava pile ( $8^\circ$ ). If a landslide had occurred during the aerial activity of the main shield, subsequent eruptions would have flown into the associated scar, overlying the previous lava succession in unconformity, which is not observed. Similarly, the sequence of the second shield is exposed on the whole width of Tahiti northern half as a succession of volcanic units without major interruption by large structures of landslide type. Flows intercalated in the base of the second shield are dated at  $0.85 \pm 0.01$  Ma, ruling out any interruption between the two volcanic stages [Hildenbrand *et al.*, 2004]. The age of the northern landslide is thus precisely constrained between  $0.85 \pm 0.01$  Ma and  $0.87 \pm 0.02$  Ma.

[29] 2. The discrepancy between the volumes estimated may be explained by the high porosity of the deposits and by the incorporation of recent sediments in the estimation of the DA volume. Significant amounts of sediments are, indeed, exposed close to the island northern shore (Figure 2, Figure 3, and profile 4 in Figure 5). Quantitative morphological studies on Tahiti drainage systems also show that a minimum volume of  $150 \text{ km}^3$  of volcanic material has been removed from the northern aerial slope of the island by erosion processes over the past 500 kyr [Hildenbrand, 2002].

[30] Tahiti thus reasonably experienced a single main northern landslide episode during its aerial evolution. Although the volume of the landslide and the area covered by the deposits have to be considered as broad estimates, the values obtained ( $V$  between  $400 \text{ km}^3$  and  $800 \text{ km}^3$ ,  $A$  about  $2950 \text{ km}^2$ ) fall on the trends predicted by Dade and Huppert [1998], suggesting a typical rockfall behavior. The detailed bathymetric analyses presented herein provide further constraints on the landslide mechanisms.

[31] The existence of debris material including flow structures is fairly obvious over the whole width of the northern DA, but these appear to have been further buried and deformed by the displacement of large blocks in the central part. Note that the two distinct facies may not have been produced by a single flow process, since the development of

flow structures on large distances require the existence of sustained pore pressures in the moving mass [Major, 1997], whereas the overall limited spreading of large blocks in the proximal part of the deposits suggests a rapid loss in energy possibly driven by block interactions [e.g., Mitchell *et al.*, 2002].

[32] Tahiti huge northern landslide thus likely developed through two main successive shots. The destabilization first involved the failure of the northern flank on a width of 25 km, producing avalanches of moderate-sized debris including a few blocks (Figures 2 and 3). The debris spread on a large area, but their submarine run-out was significantly concentrated along the lateral rims of the landslide, yielding the development of longitudinal ridges and pressure ridges flow structures. Then, the detachment and subsequent displacement of large individual blocks mainly occurred in the central part. This important change is likely an immediate consequence of the early run-out history, which had removed a significant amount of material from the island slope, especially along the lateral parts of the landslide structure. Most of the main shield northern flank may then have been detached from the surrounding topography, and thus susceptible to enhanced gravitational instability. The huge blocks mainly displaced to the north on a relatively short distance, forming a hummock. A few of them, however, run on an important distance toward NE.

## 6.2. Comparison With Other Oceanic Islands

[33] Individual debris-avalanches with volumes of several hundreds of cubic kilometers have been extensively recognized offshore the Hawaiian Islands [Moore *et al.*, 1989, 1994; Normak *et al.*, 1993; Mitchell *et al.*, 2002], around the western Canary Islands [Teide Group, 1997; Urgeles *et al.*, 1999; Masson *et al.*, 2002; Mitchell *et al.*, 2002], and to the south of Tahiti Island [Clouard, 2000; Clouard *et al.*, 2001]. Each DA is generally associated with a landslide event, but some destabilizations appear more complex, since multiple events can produce an apparent unique main unit, while a given landslide episode may produce distinct facies [e.g., Masson *et al.*, 2002], as shown in the present study.

[34] Two types of DA deposits are mainly recognized along the Hawaiian Ridge: (1) widespread DA including huge blocks detached close to present sea level and displaced up to 120 km from

their source zone (e.g., in the case of S-Kona and Nuuanu landslides [Moore *et al.*, 1989; Normak *et al.*, 1993, Mitchell *et al.*, 2002]) and (2) less voluminous DA composed of smaller-sized material, which generally form elongated depositional lobes (e.g., Alika 2 [Lipman *et al.*, 1988; Mitchell *et al.*, 2002]). Debris-avalanche deposits recognized around the Canary Islands are overall similar to the second Hawaiian type [e.g., Urgeles *et al.*, 1999; Mitchell *et al.*, 2002], whereas DA products recognized to the south of Tahiti appear more chaotic and include a significant number of kilometeric blocks [Clouard *et al.*, 2001].

[35] The two contrasted facies here evidenced in the Tahiti northern landslide deposits fall into the main types recognized elsewhere. The small-sized debris represented on the whole width of the island northern submarine flank show similarities with the products generated by Canarian landslides, including the presence of well-developed flow structures. The important concentration of large blocks exposed to the north of Tahiti is, however, comparable to the case of some voluminous Hawaiian DA, but the size of the blocks here recognized does not exceed 5 km, while the dimensions of individual blocks produced by extreme landslides on the Hawaiian Ridge reach up to 30 km across (e.g., the Tuscaloo seamount [Moore *et al.*, 1989; Normak *et al.*, 1993]).

[36] Tahiti northern landslide products extend to distances between 50 km and 70 km from the island shore, which is similar to the DA recognized to the south of Tahiti [Clouard *et al.*, 2001], but significantly lower than in the case of Hawaiian and Canarian landslides, likely due to the shallower depth of the oceanic seafloor around Tahiti.

[37] However, the bathymetric data here presented clearly show a reduced mobility of the submarine products in the central part of the landslide ( $d < 50$  km) with respect to the lateral parts ( $d$  up to 70 km to the NW and 60 km to the NE), which is a singular characteristic. To the north of Tahiti, this is associated with a gradual change in the orientation of transversal pressure ridges, indicating a bifurcation of the DA displacement to the NE during the early history of the submarine run-out. These peculiar characteristics likely result from the presence of Tetiaroa old eruptive complex, which may have acted as a natural barrier partly diverting the submarine flow of the avalanche products. The displacement of large blocks also appears reduced to the north of the island ( $d < 35$  km), but this can be associated with the lateral spreading of the

moving mass, favored by the absence of significant lateral confinement during the late evolution of the landslide run-out. However, large blocks visibly moved on a greater distance to the NE, which likely indicates that the oceanic seafloor locally had a greater slope in this direction, possibly influenced by the presence of Tetiaroa eastern submarine slope.

[38] Tahiti northern landslide was immediately followed by the construction of a second shield within the depression, as observed in the post-collapse evolution of many other oceanic islands [e.g., Navarro and Coello, 1989; Gillot *et al.*, 1994; Presley *et al.*, 1997]. This volcanic edification first occurred to the north, despite the NW displacement of the Pacific plate over the Society hot spot. The huge northern landslide here evidenced thus strongly controlled the late volcano-structural evolution of the island by capturing volcanic activity. In contrast with the case of other oceanic islands such as Reunion Island or Tenerife Island, Tahiti northern flank did not experience repeated failures during the aerial evolution of the eruptive complex. Specifically, the absence of significant chaotic units in the prolongation of the Papenoo valley outlet (Figures 2 and 3) rules out the eventuality of a more recent huge northern landslide as proposed by Clément *et al.* [2003]. The fan-shape and the smooth aspect of the superficial accumulations suggest, in contrast, that the basin evolved through regular erosion induced by a long exposition to a heavy rainfall tropical climate [Gillot *et al.*, 2004].

## 7. Conclusions

[39] The present bathymetric study demonstrates the existence of a major catastrophic northern landslide event during Tahiti-Nui aerial history, as previously proposed on the basis of on-land data [Gillot *et al.*, 1993; Hildenbrand *et al.*, 2004]. The landslide products are exposed at distances ranging between 50 km and 70 km from the island shore, and have a total volume estimated at  $800 \text{ km}^3$ . Two main types of DA facies are recognized: (1) small-sized debris including flow structures, mainly exposed along the lateral rims of the landslide, and (2) a concentration of large blocks composing the central part of the island submarine slope. The detailed bathymetric analyses suggest that the landslide first involved the rupture of the island flank on a width of 25 km. It was immediately followed by the detachment and subsequent run-out of large blocks in the central part of the landslide. The DA

products were overlain by subsequent volcanic flows, evidenced by the presence of a smooth surface standing at a mean depth of 1500 m. The on-land and offshore analyses suggest a listric fault geometry for the landslide scar, allowing an estimation of the slide volume between about 400 km<sup>3</sup> and 450 km<sup>3</sup>. In comparison with huge landslides recognized around other oceanic islands, the northern landslide here considered is characterized by a reduced mobility, especially in its median part. This was likely influenced by the presence of Tetiaroa older eruptive complex, which may have acted as a natural barrier partly diverting the submarine flow of the avalanches. Tahiti-Nui northern and southern landslides have been favored by a concentration of the magmas through a main E-W rift zone, which induced a strong N-S dilatation of the volcanic edifice. The huge northern landslide controlled the later volcanic evolution of the island, since subsequent activity migrated to the north, despite the displacement of the plate toward NW. This study highlights the importance of landslides during the geological history of French Polynesian volcanoes, and reinforces the ubiquity of huge lateral destabilizations during the eruptive evolution of oceanic islands.

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