Sedimentary fabric characterised by X-ray tomography: A case-study from tsunami deposits on the Marquesas Islands, French Polynesia

Raphael Paris, Simon Falvard, Catherine Chagué, James Goff, Samuel Etienne, Pascal Doumalin

To cite this version:

Raphael Paris, Simon Falvard, Catherine Chagué, James Goff, Samuel Etienne, et al.. Sedimentary fabric characterised by X-ray tomography: A case-study from tsunami deposits on the Marquesas Islands, French Polynesia. Sedimentology, 2020, 67, pp.1207-1229. 10.1111/sed.12582 . hal-02005135

HAL Id: hal-02005135
https://hal.science/hal-02005135

Submitted on 12 Nov 2020

Sedimentary fabric characterised by X-ray tomography: A case-study from tsunami deposits on the Marquesas Islands, French Polynesia

Raphaël Paris[1], Simon Falvard[1,2], Catherine Chagué[3], James Goff[4], Samuel Etienne[5], and Pascal Doumalin[6]

(1) Université Clermont Auvergne, CNRS, IRD, OPGC, Laboratoire Magmas et Volcans, F-63000 Clermont-Ferrand, France.

(2) Institute of Seismology and Volcanology, Graduate School of Science, Hokkaido University, N10W8 Kita-ku Sapporo, Hokkaido 060-0810, Japan.

(3) School of Biological, Earth and Environmental Sciences, UNSW Sydney, Sydney, NSW 2052, Australia

(4) PANGEA Research Centre, UNSW Sydney, Sydney, NSW 2052, Australia.

(5) EPHE, PSL, CNRS, LETG, 15 boulevard de la mer, 35800 Dinard, France.

(6) Institut P' UPR 3346 CNRS, Université de Poitiers – ENSMA. F-86962 Futuroscope Chasseneuil, France

Associate Editor – Pedro Costa

Short Title – Fabric of tsunami deposits

ABSTRACT

X-ray tomography is used to analyse the grain size and sedimentary fabric of two tsunami deposits in the Marquesas Islands (French Polynesia, Pacific Ocean) which are particularly exposed to trans-Pacific tsunamis. One site is located on the southern coast of Nuku Hiva Island (Hooumi) and the other one is on the southern coast of Hiva Oa Island (Tahauku). Results are compared with other techniques such as two-dimensional image analysis on bulk samples (particle analyser) and anisotropy of magnetic susceptibility. The sedimentary fabric is characterised through three-dimensional stacks of horizontal slices (following a vertical step of 2.5 mm along the cores), while grain-size distribution is estimated from two-dimensional vertical slices (following a step of 2 mm). Four types of fabric are distinguished: (a) moderate to high angle (15 to 75°); (b) bimodal low-angle (<15°); (c) low to high angle with at least two different orientations; and (d) dispersed fabric. The fabric geometry in a tsunami deposit is not only controlled by the characteristics of the flow itself (current strength, flow regime, etc.) but also sediment concentration, deposition rate and grain-size distribution. There is a notable correlation between unimodal high-angle fabric – type (a) – and finely-skewed grain-size distribution. The two tsunami deposits studied represent two different scenarios of inundation. As demonstrated here, X-ray tomography is an essential method for characterising past tsunamis from their deposits. The method can be applied to many other types of sediments and sedimentary rocks.

Keywords Grain size, Marquesas Islands, sedimentary fabric, tsunami deposits, X-ray tomography,

INTRODUCTION

Despite considerable progress over the last decade, the interpretation of tsunami deposits still suffers from a lack of both qualitative and quantitative criteria that would allow for a better description of flow characteristics (e.g. Chagué-Goff et al., 2011; Goff et al., 2012; Sugawara et al., 2014; Falvard & Paris, 2017; and references therein). Little attention has been paid to the fabric of tsunami deposits. The fabric of a sedimentary formation corresponds to the spatial arrangement of its grains (Sander, 1930) and its value in deducing depositional processes has been emphasised by early workers (e.g. Dapples & Rominger, 1945; Rusnak, 1957; Hand, 1961; Rees, 1968). Anisotropy of magnetic susceptibility (AMS) is commonly used to infer fabric patterns from the magnetic fabric (e.g. Rees, 1965; Taira & Lienert, 1979). The technique has been applied to different types of sedimentary rocks and soft sediments, including tsunami deposits (e.g. Wassmer et al., 2010; Cuven et al., 2013; Schneider et al., 2014; Kain et al., 2017). Direct measurements of grain orientation on thin sections under the microscope give more reliable results, but the geometry of the plane of section introduces uncertainties and the technique is time-consuming (Taira & Lienert, 1979). As stated by Rees (1965): "any rapid method of finding preferred grain orientation is, therefore, potentially of great interest".

The observed grain orientation in sediment reflects a final state of deposition and depends on different parameters related to sediment (grain size, shape, density, sorting, etc.), bed roughness and the flow itself (regime, sediment concentration, etc.). The primary fabric corresponds to the grain preferred orientation during transport and is particularly well-preserved in highly-concentrated flows that settle rapidly. When grains settle more slowly as suspension fallout, they might be reoriented by rolling or sliding near the bed (Gupta et al., 1987). Thus, the observed fabric does not always reflect the primary fabric. X-ray tomography (XRT) provides a unique opportunity to characterise the three-dimensional structure and texture of rocks and sediments, as demonstrated by its recent application to tsunami deposits (Falvard & Paris, 2017, Falvard et al., 2018). This study characterises in detail the vertical variations of grain size and clast fabric of tsunami deposits in the Marquesas Islands (French Polynesia) using 2D and 3D analyses at the grain-scale.

TSUNAMIS IN THE MARQUESAS ISLANDS

The Marquesas Islands are located in French Polynesia (South Pacific Ocean) *ca* 1400 km north-east of Tahiti and *ca* 4700 km from the nearest continent (Fig. 1). Over the past 26 kyr, four successive phases of coral reef growth were interrupted by periods of sea-level rise and reef drowning and thus the reefal shelf around the islands is poorly developed (Cabioch et al., 2008; Montaggioni et al., 2016). The youngest reef terrace, dated 9 to 9.6 ka, is now at 60 to 55 m water depth on the foreslope of the islands. Reef building has stopped over the past 9 ka. The largest islands have a shield-volcano morphology dissected by deep valleys that exit to the sea as narrow open bays. The coastline of the Marquesas Islands is dominated by rocky coasts with plunging cliffs or fringing shore platforms, whereas beaches and dunes are found at the mouth of the river valleys and embayments.

Due to its central position in the Pacific Ocean, the archipelago is particularly exposed to trans-Pacific tsunamis caused by earthquakes in Japan (2011), Kamchatka (1952), the Aleutian (1946 and 1957), Alaska (1964), Peru (1868, 1996 and 2001) and Chile (1837, 1877, 1922, 1960 and 2010). Since the narrow bays are not protected by outer reefs, their morphology is prone to tsunami amplification (Hébert et al., 2001). Tsunamis are part of the Marquesian culture and the local expression ‘tai toko’ refers to catastrophic wave events (Candelot, 1996). The oldest tsunami reported in the area dates back to 1806 (Candelot, 1996), and since 1837 there have been 17 reported tsunamis, seven of them with wave runups exceeding 3 m (Schindelé et al., 2006; Sladen et al., 2007; Reymond et al., 2013). The 1946 Aleutian tsunami impacted all of the islands, with runups up to 18 m in the valleys (Schindelé et al., 2006). No tropical cyclone has been ever recorded in the Marquesas Islands Archipelago since the onset of meteorological observations in 1831. This is explained by the geographical proximity of the equator inhibiting the organisation of convective clouds in spiral bands (Larrue & Chiron, 2010; Laurent & Varney, 2014).

Tsunamis have left their mark on the coastal landscapes of the Marquesas Islands. During a field survey in June 2012 the present authors noted numerous traces of sediments, driftwood and erosion by extreme sea waves at altitudes up to 36 m above sea level (a.s.l.) (Fig. 2: coral conglomerate at Hanateio, eastern coast of Tahuata Island). Coral boulders in the valleys (for example, Hooumi in Nuku Hiva and Hanamenu in Hiva Oa) represent another compelling line of evidence for tsunami inundation since there are no elevated reefs in the Marquesas. Trenches made in low-energy morpho-sedimentary systems revealed fine-grained (mud to sand) deposits fulfilling the typical trench-scale criteria of tsunami deposits (e.g. Shiki et al., 2008; Goff et al., 2012). The main sedimentary facies observed are laminated sands in a discontinuous contact overlying soil or lagoonal muds that are reworked as rip-up clasts and mud lines. Some of the sedimentary successions observed have recorded several tsunamis (for example, Haatuatua in Niku Hiva and Taipivei in Hiva Oa), including the 2011 Japan tsunami deposits that were still well-preserved in June 2012. Satellite imagery of Haatuatua Bay (eastern coast of Nuku Hiva) before and after the 2010 and 2011 tsunamis illustrates the morphological imprint of recent tsunamis on coastal landscapes (Fig. 3). A comparison between images from June 2005 and April 2013 shows erosion of the lower sand ridge, driftwood deposition up to 9 m a.s.l. (Fig. 2) and progression of the sand washover fans inland at altitudes up to 15 m a.s.l. (Fig. 3). There are no runup estimates available for the eastern coast of Nuku Hiva, but Reymond et al. (2013) reported maximum runups of 3.8 m and 4.5 m for the 2010 and 2011 tsunamis, respectively, on the southern coast.

SAMPLING SITES AND METHODS

Extensive field work aiming at reconstructing the tsunami chronology of the Marquesas Islands would cover the entire archipelago and document tens of sites with absolute dating of the different sedimentary units, but this is not the aim of the present study. This work focuses on two sites (Fig. 4): (i) on the southern coast of Nuku Hiva Island (Hooumi); and (ii) on the southern coast of Hiva Oa Island (Tahauku). Both of these sites were impacted by the 2010 and 2011 tsunamis, with wave runups of 2.5 to 3.5 m (Reymond et al., 2013). The 1946 and

1960 tsunamis were particularly high in Tahauku, with runups of 14 m and 12 m, respectively (Schindelé et al., 2006).

Hooumi is located at the end of a funnel-shaped branch of the Baie du Contrôleur (Fig. 4A). There is no river outlet, and a small lagoon has formed behind the sandy beach. The sampling site is a low altitude (<2 m a.s.l.) hand dug trench on the western side of the lagoon, 210 m from the shoreline. Tahauku is another example of a funnel-shaped bay located east of Atuona village (Fig. 4B). The site is particularly exposed to tsunami wave amplification (Hébert et al., 2001). A large trench was dug mechanically between the lagoon and the river outlet. Note that the lagoon that was still visible on the November 2004 satellite imagery (Google Earth©) has now disappeared due to successive sediment inputs from anthropic activities and tsunamis.

A complete dataset of the structure and texture of a tsunami deposit was collected in the Tahauku trench. Two sections were sampled: a shore-parallel section oriented N115° and a shore-perpendicular section oriented N190° (Fig. 5). Bulk samples of sediments were collected vertically along both sections. Sampling includes pre-tsunami soil, a 30 cm thick tsunami deposit (tsunami 2 on Fig. 5) and deposits of the 2011 tsunami.

Grain size of bulk samples was analysed using a particle analyser (Morphologi G3; Malvern Panalytical, Malvern, UK). The G3 analyser separates particles using an integrated disperser, and captures thousands of images of individual particles down to 0.5 µm and up to 1.5 mm using a microscope linked to a digital camera. Image analysis then provides quantitative parameters related to the size (for example, equivalent spherical diameter, perimeter, width, length and area) and shape of the particles (for example, aspect ratio, circularity, solidity, convexity and elongation). The method has been applied successfully to volcanic ash (Leibrandt & Le Pennec, 2015) and tsunami deposits (Ulvrova et al., 2016). Particles were captured at a focal length of 0.130 to 0.160 mm, a magnification of ×2.5, and a resolution of 5 megapixels. The dataset is then filtered at 20 µm in order to eliminate post-sampling artefacts (for example, dust), yielding particle numbers between 2800 and 11700 (Fig. 6).

The anisotropy of magnetic susceptibility (AMS) was analysed using a Kappabridge KLY-2 (Agico, Brno, Czech Republic). Samples from the Tahauku trench were collected in 2 cm sided oriented boxes, as described in Wassmer et al. (2010). Each sample was analysed in 15 directions to determine the magnitude and directions of the maximum, intermediate and minimum AMS axes. The anisotropy of each sample (i.e. each cubic box) can be represented by a triaxial ellipsoid (the maximum K1 or K_{max}, intermediate K2 or K_{int} and minimum K3 or

K_{min} axes corresponding to principal eigenvectors). The stereographic projection (lower hemisphere equal-area projection) of the three axes of the ellipsoid gives information on the preferential orientation of the ferromagnetic minerals (for example, magnetite from volcanic rocks in the case of the Marquesas Islands).

Oriented cores of tsunami deposits were retrieved in carbon fibre tubes (10 cm long and 2 cm wide), thus preserving their structure and vertical variations of texture. Roots and cobbles locally prevented coring the entire thickness of the tsunami deposit. Four cores of tsunami deposits were sampled: two cores at Tahauku (TK03-A and TK03-B on Fig. 5) and two cores at Hooumi (Ho1-A and Ho1-B on Fig. 7). Cores were scanned at the Institut P' using an X-ray tomography system (UltraTom; RX-Solutions, France) at 70 kV and 140 µA. The acquisition time per core ranged between 22 and 25 hours (eight successive scans by translating the core along the beam were necessary to cover the entire volume of each core). Reconstructed data are sets of 16 bits Tiff image files representing cross-sections of the cores (horizontal slices from top to base). Image resolution (voxel size) is 11 µm. The total number of images available for each core ranges from 7618 to 9230.

Particles (grains) were semi-automatically separated using the morphological segmentation tool of the *MorphoLibJ* collection (Legland et al., 2016) included in the *Fiji* distribution of *ImageJ* (Schindelin et al., 2012). Sedimentary fabric data were obtained from three-dimensional stacks of horizontal slices, while statistics on grain size (following a vertical step of 2 mm along the cores) and grain-size maps were calculated from a two-dimensional vertical slices of each core, using new versions of the *grainstat* and *grainmap* codes rewritten in Python 3.5 (modified from Falvard & Paris, 2017). *Blob3D* program (Ketcham, 2005) was used to obtain data on the 3D orientation of particles. Resolution and image quality allowed characterisation of the sedimentary fabric with a vertical step of 2.5 mm along the cores, which represents an eight-fold increase in spatial resolution compared to a previous study (Falvard & Paris, 2017). Fabric data were plotted as stereographic projections of the orientations of the longest grain axes (900 to 3500 grains at each step, representing a total number of >60000 grains). Particles with a short axis lower than 10 voxels were excluded in order to avoid artefacts from potential over-segmentation of some grains or from noise. The geometry of the fabric at each vertical step is inferred from the characteristics of the ellipsoid (degree of anisotropy, elongation, azimuth and plunge) of preferred grain orientation.

RESULTS

Tahauku trench

At Tahauku, two successive tsunami deposits overlying soil are preserved (Fig. 5). The upper tsunami deposit has a thickness of 15 to 20 cm and corresponds to the 2011 Tohoku-oki tsunami (as confirmed by local residents). The deposit is poorly sorted, with grain size ranging from very fine sand to pebbles, including bioclasts (fragments of shells and corals). It is difficult to observe any internal structure and bedform, due to bioturbation (note abundant roots in the deposit on Fig. 5). The lower tsunami deposit is thicker (30 cm) and structured in different subunits. Basal contact with the soil is erosive (note erosional contact at 45 to 50 cm depth on Fig. 5). Because the trench is located at the border of a former lagoon, the soil has a bimodal composition due to a mixing of mud (lagoon) and fine sand (fluvial and coastal inputs). The soil corresponds to samples 8 and 9 on Figs 5A and 6.

The lowermost tsunami subunit has an irregular thickness and consists of crudely laminated, poorly-sorted medium sand (subunit 7 on Figs 5A and 6; subunit 4 on Figs 5B and 6). The lower part of the subunit is particularly rich in heavy minerals and inversely graded (Fig. 7). This vertical grading is not uniform and rather corresponds to an inversely-graded sequence of multiple poorly-defined laminae. The upper part of the subunit displays mud clasts (from the underlying soil) and high-angle lamination dipping towards the south-west, which is associated with small variations of grain size and sorting (Fig. 7). Detailed analysis of the fabric at a vertical step of 2.5 mm reveals complex variations along the 10 cm long core (Fig. 8). Four types of clast fabric can be distinguished: (a) moderate-angle (15 to 35°) fabric oriented north-east (i.e. dipping towards the south-west); (b) bimodal low-angle (<15°) fabric (two orientations with opposite angles); (c) low to moderate angle fabric with at least two orientations; and (d) dispersed fabric. Type-b fabric has a majority of south-west/north-east orientations, but north-west/south-east orientations are recorded locally (for example, 38.5 cm depth on Fig. 8). The AMS samples near the base of the core have K_{max} axes oriented NE/ENE at angles of 5 to 15° (samples TK03-43 and TK04-48 on Fig. 5C), an orientation that is concordant with fabric obtained from XRT at a similar depth (Fig. 8). The lower part of the subunit (42 to 44 cm depth) shows a succession of b–d–a fabric, followed by a coarse-grained interval with poorly-defined fabric (40.5 to 42.0 cm depth). The upper laminated part of the core (39.5 to 35.0 cm depth) displays alternating b and d fabrics.

The aforementioned basal subunit of the tsunami deposit is deeply eroded by a chaotic coarse-grained and poorly-sorted subunit (too coarse to be sampled for XRT). Medium to coarse sand is mixed with corals and numerous pebbles over a thickness of 15 to 20 cm (subunit 6).

At a depth of 30 cm below the surface, another erosional contact marks the onset of a new phase characterised by finer sediments (Fig. 5) with abundant bioclasts (Fig. 9). The contact is fossilised by a 2 to 5 cm thick assemblage of medium sand and shells with abundant mud clasts, as confirmed by X-ray imagery (subunit 5). The relative abundance of mud clasts decreases upward and the deposit progressively turns to silty sand. As observed on the shore-perpendicular section (Fig. 5B) and XRT (Fig. 7), subunits 2 and 4 are crudely laminated: horizontal lamination at the base of subunit 4, cross-lamination in upper subunit 4, and low-angle lamination dipping seaward (towards the south-west) in subunit 2. This lamination is associated with vertical variations of grain size. However, the laminated silty sand is not homogeneous. Some laminae are coarser-grained (for example, lens of coarse sand on Figs 7 and 9) or enriched in heavy minerals (for example, at 19.5 and 22.5 cm depth on Fig. 9). Different facies of mixing between sand and clay are observed (Fig. 9): (i) interstitial clay acting as a matrix between sand grains; (ii) aggregates of mud clasts with sand grains and bioclasts intercalated; and (iii) discontinuous mudlines. As an example, the mudline sampled in core TK03-A is clearly not homogenous. Shades of grey underline variations of composition of the clayey matrix (Fig. 9). The mudline texture is an assemblage of sand and bioclasts with mud clasts that are more or less deformed and disaggregated (Fig. 10). This succession of more or less cohesive subunits shows evidence of post-tsunami deformation (Fig. 11).

In terms of fabric, subunits 2 and 4 do not share the same characteristics. In subunit 4, the AMS ellipsoid of sample TK03-23 has a high degree of anisotropy and an unusual oblate geometry; the K_{max} dips at 50° towards the SSW and the K_{min} is tilted 90° westward (Fig. 5C). The fabric is visible on X-ray imagery as well and the imbrication of the coarsest clasts points to a current oriented towards the north-east (landward) at relatively high angles (type-a fabric), which is concordant with the results of AMS. The resolution of the scan does not allow the development of any fabric in the mudline to be characterised quantitatively (subunit 3). In subunit 2, the orientation and weak inclination (<15°) of the magnetic fabric suggests a current weakly directed seaward. Indeed, AMS samples TK03-16 and TK04-23 have K_{max} that are oriented towards the south-west and west, respectively (Fig. 5C).

Hooumi trench

At Hooumi, the 2010 and 2011 tsunamis deposited fine patches of sand on the ground and there is no notable sedimentary unit related to these two events in the local stratigraphy. However, coral boulders along the river (Fig. 2B) and a massive sand unit overlying soil (Fig. 12) attest to deposition from at least one larger-magnitude tsunami. There is almost no evidence of pedogenesis on top of this tsunami sand, suggesting that it corresponds to a recent event. The 1946 tsunami is a candidate but its runup at Hooumi was similar to the 2010 and 2011 runups (<3 m; Schindelé et al., 2006).

The tsunami deposit is up to 40 cm thick (Fig. 12). Planar to oblique crude lamination is visible over its entire thickness. The thinnest laminae are enriched in silt-sized material. Pebbles and roots at the base (43 to 32 cm depth) and in the central part of the deposit (23 to 18 cm depth) introduced gaps in the XRT sampling. However, the two cores retrieved (Ho01-A and Ho01-B) provide a high-resolution characterisation of grain size and fabric over two intervals of 10 cm (Figs 12 and 13). Subtle vertical variations of grain size and sorting are detected. Maximum grain size typically ranges between 0.4 mm and 0.6 mm, with three peaks higher than 0.8 mm. Sediment is poorly sorted, especially at the base of the two cores. There is no vertical grading except for a slight normal grading at the base of core Ho01-A (Fig. 12).

As in Tahauku, four types of clast fabric are distinguished (Fig. 13): (a) high-angle (25 to 75°) fabric; (b) bimodal low-angle (<15°) fabric (two orientations with opposite angles); (c) low to high angle fabric with at least two orientations; and (d) dispersed fabric. From base to top, different trends of fabric are identified. The lower part of Ho01-B (33 to 30 cm depth) is poorly organised (type-d fabric), except at the level of a silty lamina (type-b fabric weakly oriented NNE or SSW). The lamina itself has a type-b fabric dominantly oriented NNE. From 30.0 to 26.5 cm depth, the data here record a progressive reversal from high-angle (type a) fabric oriented north-east (i.e. dipping towards the south-west) to bimodal high-angle fabric (type c), and finally high-angle fabric oriented SSW. After a short interval of disperse fabric (type d), clasts are weakly inclined (type b) with north-west or south-east orientations (25.0 to 23.5 cm depth). Core Ho01-A (Fig. 13) starts with a phase of poor organisation associated with normal grading. The sediment then adopts a clear high-angle fabric (type a) oriented south-east to SSW (i.e. rotation of the plunge from NNW to NNE between 16.5 cm and 14.5

cm depth on Fig. 13), before returning to a dispersed or weakly organised fabric (14.5 to 9.5 cm depth).

DISCUSSION

Types of sedimentary fabric

As demonstrated by the results presented above, X-ray tomography (XRT) is a powerful technique for characterising the fabric of unconsolidated sediments such as tsunami deposits. The method used here allows a full 3D quantitative analysis of the fabric at a high-resolution (vertical step of 2.5 mm). The small-scale variations of fabric, together with grain size and sorting, would have been impossible to detect with other techniques, such as AMS. At both sites, four types of fabric were distinguished (Fig. 14):

(i) *Type-a fabric* represents moderate to high angle fabric (15 to 35° at Tahauku; 25 to 75° at Hooumi) with a well-defined orientation. Considering the funnel-shaped morphology of the Hoomi and Tahauku valleys, it can be assumed that the tsunami current was oriented parallel to the axis of the valley, i.e. directed towards the north-west at Hooumi and towards the north-east at Tahauku (Fig. 4). Thus, type-a fabric recorded in the lower part of core TK03-B is flow-parallel and directed landward (Fig. 8). Type-a fabric in the middle part of Ho01-B is characterised by high angles oscillating between flow-parallel and flow-oblique orientations (Fig. 13). In Ho01-A the interval of type-a fabric is parallel to oblique, with a notable seaward orientation. Flow-transverse orientations (i.e. perpendicular to the axis of the valley) are apparently rare in type-a fabric.

(ii) *Type-b fabric* is characterised by a low inclination of the grains (<15°) following two opposite orientations. Thus, the direction of the current cannot be determined if it is assumed that the fabric is parallel to the flow direction. At Tahauku, the type-b fabric is oriented parallel to the inferred flow direction (oriented south-west/north-east), except in a very short interval of flow-transverse fabric (south-east/north-west orientation at 38.5 cm depth on Fig. 8). The type-b fabric at Hooumi is parallel or slightly oblique to the flow (Fig. 13). Type-a and type-b fabrics have similar degrees of anisotropy and elongation of the ellipsoid of grain orientation (as defined by Benn, 1994) but they are different in terms of angle of fabric (cf. plunge on fig. 14).

(iii) *Type-c fabric* is a low to high angle fabric with at least two different orientations. Both at Hooumi and Tahauku, type-c fabric is observed on short intervals (<1 cm thick) between other types of fabric. It is thus a transitional fabric: transition between type-a and type-d fabric in Ho1-A, short interval in a type-a fabric in Ho1-B (Fig. 13). More type-c fabric is present at Hooumi than at Tahauku. The mean degree of anisotropy is slightly higher than the other types of fabric (Fig. 14A), while the degree of elongation is notably lower than types a and b (Fig. 14B).

(iv) *Type-d fabric* is a group of dispersed fabrics resulting from a random orientation of the grains. Type-d fabric usually displays low angles of inclination of individual grains, as for type-b fabric. Rare examples of moderate-angle disperse fabric correspond to transitional c–d fabrics. As for type c, type-d fabric has a low degree of elongation compared to type-a and type-b fabrics (Fig. 14). Type-d fabric is dominant in the upper part of core Ho01-A (Fig. 13). It is found in alternation with type-b fabric in the lower part of core Ho01-B (Fig. 13) and in the upper part of core TK03-B (Fig. 8).

Influence of the grain-size distribution on sedimentary fabric

According to experimental data (e.g. Rees, 1983; Gupta et al., 1987), the development of a sedimentary fabric in sandy deposits does not necessarily relate to the strength of the current, because it also depends on sediment concentration and grain-size distribution. Studies of the magnetic fabric of tsunami deposits inferred from AMS reached similar conclusions (Wassmer et al., 2010; Schneider et al., 2014).

High concentration and rapid deposition of sediment can even hinder the development of an anisotropic fabric because of significant interaction between touching grains and a lack of space for spatial organisation (Hiscott & Middleton, 1980; Falvard & Paris, 2017). Schneider et al. (2014) suggested that the primary fabric is better developed where fine-grained particles (silts and clays) are mixed with sands. The relationship between the preservation of a primary fabric and a finely-skewed grain-size distribution is particularly well-illustrated in the case of Tahauku (Fig. 15), where sand is mixed with finer sediments from a lagoon. In the lower part of core TK03-B, the onset of a type-a fabric with angles up to 35° is related to increased coarse sand fraction and high values of skewness. This is concordant with the observations of Capaccioni & Sarocchi (1996) who used XRT to characterise the vertical variations of the fabric of an ignimbrite. The degree of preferred orientation of the elongated grains of the ignimbrite is correlated with the percentage of matrix. At Hooumi, vertical variations of grain-size distribution are less pronounced (Fig. 12), but two of the three major peaks of skewness are found in sediments with a type-a fabric (Fig. 16). Thus, the development of type-a fabric in a tsunami deposit is probably controlled by interactions between medium to coarse sand and fine-grained fractions (silts, clays) and not only by the characteristics of the flow itself (current strength, flow regime, etc.).

However, finding relationships between sediment sorting and fabric is far from evident. Peaks of sorting index (i.e. very poor sorting) at the base of the two Hooumi cores coincide with a disperse fabric (Fig. 16). The short episode of normal grading identified in core Ho01-A (17.5 to 16.5 cm depth) is characterised by an upward increase of the sorting (cf. decreasing sorting index on Fig. 16), low skewness and poorly-defined fabric (dominant type-c fabric).

Flow-parallel versus flow-transverse fabric

The sedimentary fabric observed in the two tsunami deposits is oriented either parallel or oblique to the inferred flow direction. Studies on the magnetic fabric of tsunami deposits inferred from AMS reported both flow-parallel and flow-transverse orientations (Wassmer et al., 2010; Paris et al., 2014; Schneider et al., 2014; Falvard & Paris, 2017). Falvard & Paris (2017) combined AMS and XRT and found dominant low-angle flow-transverse fabrics in a tsunami deposit. However, the quality of the scans both in terms of resolution and contrast did not allow characterisation of the small-scale vertical variations of fabric.

Direct comparison between AMS and XRT data shows that the magnetic fabric broadly illustrates the flow-parallel fabric at the base of core TK03-B (Fig. 8). However, XRT data reveal more complex patterns of fabric with a transition from low-angle (type b) or disperse fabric (type d), to a well-defined moderate-angle fabric (type a) indicating a current oriented towards the north-east (landward). At Tahauku, the fabric is mainly parallel to the flow direction. Flow-transverse fabric between 38 cm and 40 cm depth (Fig. 8) coincides with low values of skewness and an upward decrease of the sorting (Fig. 15).

In core Ho01-B, the data here record a transition from high-angle flow-oblique fabric oriented north-east to flow-oblique fabric oriented SSW (29 to 26 cm depth on Fig. 13). Interestingly, the current reversal is marked by type-c fabric displaying the two opposite orientations. Type-b fabric at the top of Ho01-B is a typical example of flow-parallel fabric. Small-scale variations detected between 18.0 cm and 14.5 cm depth illustrate short-lived transitions from flow-parallel to flow-oblique fabric in a current directed seaward (backwash).

Flow-parallel fabric is common for sands transported at high sediment concentration and rapidly deposited (e.g. Rees, 1968, 1983; Hiscott & Middleton, 1980; Gupta et al., 1987; Deprez, 2016). A high deposition rate is required for preserving this primary fabric. Such conditions are likely to be reproduced in tsunami waves transporting large amounts of sediment, especially during the inundation phase (e.g. Paris et al., 2009; Goto et al., 2014). Hiscott & Middleton (1980) also observed flow-parallel fabric with angles commonly >20° in laminated sandstones formed by turbidity currents. Gupta et al. (1987) obtained moderate-angle (11 to 25°) flow-parallel fabric in sands deposited in the upper-stage plane-bed phase, with a minor flow-oblique mode, while Baumann et al. (2017) observed flow-parallel fabric turning to flow-oblique fabric in the distal part of a storm washover deposit.

The onset of flow-oblique fabric indicates a reduction of the bed shear stress and a re-orientation of the grains by rolling or sliding near the bed (Gupta et al., 1987). In the data herein, the ellipsoids of flow-parallel and flow-oblique fabrics are not significantly different in terms of angle of fabric, isotropy and elongation. The influence of parameters such as sediment concentration, grain size or flow regime on the production of fabric has been tested in experiments on sheared dispersions of sand. Allen (1984) suggested that the vertical variability of fabric reflects variations of flow regime. Poorly-sorted sands deposited in the lower plane-bed phase show flow-parallel orientation patterns for the finer grains (<0.7 mm), and both flow-parallel and flow-transverse orientations for the coarser grains (>0.7 mm). Rees (1983) found that the flow-parallel fabric is preserved at low (1 to 2%) and high-sediment concentration (>11%), while the fabric becomes transverse for some intermediate concentrations (3 to 8%). At intermediate concentration, the production of a flow-parallel fabric is prevented by frequent ‘grain to grain’ collisions. At higher concentration, a reduction of the distance between colliding grains creates transfers of angular momentum and does not allow the development of a flow-oblique fabric (Rees, 1983), thus resulting in flow-parallel or disperse fabric. The vertical variations of fabric observed in tsunami deposits could reflect similar changes in sediment concentration (sediment pulses) and aggradation rate through time. Transitions from flow-parallel to flow-oblique fabric could be related to the deceleration of the flow and decrease of the sediment concentration, although local effects due to the topography (for example, wave reflection in the narrow valleys and bed roughness) should not be excluded.

Variations of the angle of fabric

Type-a fabric has imbrication angles of 15 to 35° at Tahauku and 25 to 75° at Hooumi. Angles of imbrication higher than 20° are common in sands rapidly deposited by sediment gravity flows (e.g. Hiscott & Middleton, 1980), and it is actually not surprising to have such high-angle fabric in tsunami deposits. Cheel (1991) interpreted the bimodality and cyclic variations of the imbrication angle (from almost 0 to 35°) as variations of the strength of an oscillatory current during a storm. Deposits formed by unidirectional currents apparently display few variations of the orientation and angle of imbrication. Experimental upper plane beds have upcurrent imbrication angles ranging between 11° and 25°, whereas lower plane beds have angles lower than 15° both in upcurrent and downcurrent directions (Gupta et al., 1987). Low-angle type-b fabric (<15°) observed in the tsunami deposits displays similar bimodal orientation patterns. If the results of laboratory experiments are extrapolated, type-b and type-a fabrics could correspond to phases of subcritical flow regime and near-supercritical flow regime, respectively. Indeed, the Froude number of a tsunami during its phase of inundation inland typically ranges between 0.7 and 2.0 (Matsutomi et al., 2010), i.e. at the transition between subcritical and supercritical conditions.

However, the vertical variation of the angle of fabric is not an unequivocal proxy of the transport and deposition mechanisms, because it also depends on the grain-size distribution and shape of the grains. As discussed above, the grain-size distribution has an influence on the development of a sedimentary fabric. Moderate to high angle fabric (such as type-a fabric) is better preserved in sediments that have a finely-skewed grain-size distribution. There is a remarkable positive correlation between the skewness of the grain-size distribution and the angle of fabric, especially at Tahauku (Fig. 15). Higher values of skewness at Tahauku, compared with Hooumi, are due to larger inputs of fine sediments. Consequently, the fact that the angle of fabric is generally higher at Hooumi than at Tahauku (Figs 15 and 16), cannot be explained only by different sediment sources and grain-size distribution between the two sites. A faster deposition rate at Hooumi is the most plausible explanation.

Two different scenarios of inundation

Detailed analysis of the vertical variations of grain size and fabric enable a scenario to be proposed for the two tsunamis. Core TK03-B, which was sampled in the lower part of the Tahauku tsunami deposit, represents the initial stage of inundation. The lowermost 4 cm (44 to 40 cm depth) are characterised by an inversely-graded sequence of poorly-defined laminae and a flow-parallel fabric. The progressive increase of the current strength and sediment concentration is illustrated by bimodal low-angle (type-b) fabric turning to disperse fabric (type-d). Type-a fabric represents the peak of aggradation of this first pulse (Fig. 8). The upper part of the core displays high-angle backset laminae associated with alternating type-b and type-d fabric. Both flow-parallel and flow-oblique trends are observed in type-b fabric, depending on the distribution of the shear stress in the boundary layer. The main inrush of inundation starts with a thick disorganised subunit of coarse sand with pebbles (Fig. 5) that is not suitable for a microtextural analysis. The pebbles are not preferentially oriented.

At this stage, the small beach is probably deeply eroded and sediment from other sources is incorporated into the deposit (sediment from the bay and from the riverbed). Indeed, the upper laminated sand sampled in core TK03-A is finer-grained (silty sand mixed with clay) than the underlying subunits (Fig. 6) and particularly rich in marine bioclasts. The heterogeneous texture of the mudlines (Fig. 10) confirms the conclusion of Falvard & Paris (2017) who proposed that they represent the friction-dominated region of a high-energy erosive current rather than a calm settling of clay. The mudline corresponding to subunit 3 (Figs 5 to 10) marks the onset of the backwash, as confirmed by a seaward-oriented fabric in the laminated sand above the mudline (AMS samples TK04-23 and TK03-16 on Fig. 5c).

The characteristics presented above (for example, different subunits separated by erosive discontinuities, a diversity of sediment sources and well-developed mudlines) point to a large event, i.e. larger than the effects reported for the 2010 and 2011 tsunamis in the Marquesas. At Tahauku, the 2011 tsunami had a maximum wave runup of 2.8 m at 90 m from the shoreline (Reymond et al., 2013) and left a 15 cm thick deposit of coastal sand and pebbles (Fig. 5). The 1946 and 1960 tsunamis are good candidates for the deposit studied here. The 1946 tsunami penetrated the Tahauku valley to a distance up to 830 m with a runup of 14.6 m (Okal et al., 2002) and the 1960 tsunami runup at Tahauku was 12 m (Schindelé et al., 2006).

At Hooumi, the 2 m high waves of the 1946 tsunami followed the Hooumi riverbed up to 660 m inland and deposited coral boulders up to 12 tons at 100 m from the shoreline (Okal et al., 2002). The base of the boulders is buried in the tsunami deposit studied here, suggesting that it is the same event, which is consistent with the absence of pedogenesis on top of the deposit. The coarse-grained basal subunit including pebbles (not sampled for XRT) is overlain by a 20 to 30 cm thick succession of laminated sand. This crude lamination indicates periodical variations of the aggradation rate due to successive sediment pulses that are associated with subtle variations in grain size, sorting and fabric. As observed in Tahauku, the common alternating type-b and type-d fabrics illustrate these variations of sediment concentration and deposition rate. There are no erosive discontinuities between each new pulse, even during the current reversals. A first reversal at 27 cm depth (Fig. 13) is characterised by type-a fabric oriented north-east to type-a fabric oriented SSW, with transitional type-c fabric in between. Another phase of backwash is identified in the upper part of the tsunami deposit, with type-a fabric being notably directed seaward from 16.7 to 14.5 cm depth on core Ho01-A. The association between high-angle type-a fabric and backwash currents at Hooumi is in favour of a high deposition rate. The second backwash is preceded by a phase of suspension fallout, as evidenced by normally-graded sediments with poorly-defined, flow-oblique fabric (17.5 to 18.5 cm depth). This is consistent with a decreasing concentration and deposition rate at the end of the tsunami uprush. The fabric observed is not primary, as the grains settling down are reoriented oblique to the flow by rolling near the bed.

The two tsunami deposits differ in terms of composition, texture and structure, and they represent two different scenarios of inundation. Although the tsunami runup was considerably higher at Tahauku (14.0 m compared to 2.5 m at Hooumi during the 1946 tsunami), the two deposits have a similar thickness (30 to 40 cm). The Hooumi deposit was built by pure aggradation, while the Tahauku deposit is internally structured in several subunits separated by erosive discontinuities. The relatively thick deposit at Hooumi can be explained by: (i) a limited amount of sediment loss during backwash, resulting in a paucity of sediment being re-deposited offshore (which is consistent with the type-a fabric and high deposition rate of the backwash deposits onshore); and/or (ii) more sediment availability when the tsunami occurred (for example, a beach-dune system more developed than today). This example illustrates the limitation of using the thickness of a palaeo-tsunami deposit as an indicator of its intensity, especially in the absence of information concerning the morpho-sedimentary setting prior to tsunami inundation.

CONCLUSION

Due to their central position in the Pacific Ocean, the Marquesas Islands represent a natural laboratory for studies on the sedimentary record of trans-Pacific tsunamis. The islands have a low-moist tropical climate and tsunami deposits are well-preserved. Only two sites were investigated here, but a regional study could provide a detailed reconstruction of the chronology of tsunamis generated by seismic mega-ruptures around the Pacific Ocean. The quality and relevance of the data obtained on the two tsunami deposits confirm that X-ray tomography (XRT) is a powerful technique for characterising the grain-size distribution and sedimentary fabric of tsunami deposits, as well as other types of sedimentary formations (for example, turbidites and pyroclastic flow deposits). Unlike other techniques such as anisotropy of magnetic susceptibility (AMS) or thin sections, XRT reveals the true three-dimensional fabric. Further investigations will help to better define relationships between the geometry of the fabric, the characteristics of the flow (current strength, flow regime and sediment concentration), the depositional processes, and the characteristics of the sediments at the source.

ACKNOWLEDGEMENTS

This work was funded by the Contrat de Projet Etat - Polynésie française 2009-2013, project RINALPOF (Les risques naturels extrêmes sur les littoraux de la Polynésie française : archives géologiques – modélisation – réduction des risques) hosted by Université de la Polynésie Française (UPF). The authors are particularly grateful to Yannick Guéhenneux, Jérôme Bascou, and Krzysztof Suchorski (LMV). Philip Kempf, Paolo Marco de Martini, and Pedro Costa are thanked for their relevant and laudatory reviews. This is ClerVolc Laboratory of Excellence contribution number 324.

REFERENCES

Allen, J.R.L. (1984) *Sedimentary structures, their character and physical basis*, vol. 1. Elsevier, New York, 593 pp.

Baumann, J., Chaumillon, E., Bertin, X., Schneider, J.L., Guillot, B., Schmutz, M. (2017) Importance of infragravity waves for the generation of washover deposits. *Marine Geology* **391**, 20-35.

Benn, D. (1994) Fabric Shape and the Interpretation of Sedimentary Fabric Data. Journal of *Sedimentary Research* **64**, 910-915.

Cabioch, G., Montaggioni, L., Frank, N., Seard, C., Sallé, E., Payri, C., Pelletier, B., Paterne, M. (2008) Successive reef depositional events along the Marquesas foreslopes (French Polynesia) since 26 ka. *Marine Geology* **254**, 18-34.

Candelot, J.L. (1996) Tai Toko ! ou l'imminence d'un cataclysme dans les Marquises. Association des historiens et géographes de Polynésie française et Centre territorial de recherche et de documentation pédagogique de Polynésie française, Éd. Polyèdre Culture, Tahiti.

Capaccioni, B., Sarocchi, D. (1996) Computer-assisted image analysis on clast shape fabric from the Orvieto-Bagnoregio ignimbrite (Vulsini District, central Italy): implications on the emplacement mechanisms. *Journal of Volcanology and Geothermal Research* **70**, 75-90.

Chagué-Goff, C., Schneider, J.-L., Goff, J.R, Dominey-Howes, D., Strotz, L. (2011) Expanding the proxy toolkit to help identify past events — Lessons from the 2004 Indian Ocean Tsunami and the 2009 South Pacific Tsunami. *Earth-Science Reviews* **107**, 107-122.

Cheel, R.J. (1991) Grain fabric in hummocky cross-stratified storm beds: genetic implications. *Journal of Sedimentary Petrology* **61**, 102-110.

Cuven, S., Paris, R., Falvard, S., Miot-Noirault, E., Benbakkar, M., Schneider, J.-L., Billy, I. (2013) High-resolution analysis of a tsunami deposit: Case-study from the 1755 Lisbon tsunami in southwestern Spain. *Marine Geology* **337**, 98-111.

Dapples, E.C., Rominger, J.F. (1945) Orientation analysis of fine grained clastic sediments. *Journal of Geology* **53**, 246-261.

Deprez, M. (2016) Multiscale micro-CT imaging on sediment cores: unravelling the paleoflow directions in a megaturbidite (Lake Lucerne, Switzerland). Master's dissertation, Faculty of Science, Universiteit Gent, Belgium, 89 p.

Falvard, S., Paris, R. (2017) X-ray tomography of tsunami deposits: towards a new depositional model of tsunami deposits. *Sedimentology* **64**, 453-477.

Falvard, S., Paris, R., Belousova, M., Belousov, A., Giachetti, T., Cuven, S. (2018) Scenario of the 1996 volcanic tsunamis in Karymskoye Lake, Kamchatka, inferred from X-ray tomography of heavy minerals in tsunami deposits. *Marine Geology* **396**, 160-170.

Goff, J.R., Chagué-Goff, C., Nichol, S., Jaffe, B., Dominey-Howes, D. (2012) Progress in palaeotsunami research. *Sedimentary Geology* **243–244**, 70-88.

Goto, K., Hashimoto, K., Sugawara, D., Yanagisawa, H., Abe, T. (2014) Spatial thickness variability of the 2011 Tohoku-oki tsunami deposits along the coastline of Sendai Bay. *Marine Geology* **358**, 38-48.

Gupta, G.D., Parkash, B., Garde, R.J. (1987) An experimental study of fabric development in plane-bed phases. *Sedimentary Geology* **53**, 101-122.

Hand, B.M. (1961) Grain orientation in turbidites. *Compass* **38**, 133-144.

Hébert, H., Schindelé, F., Heinrich, P. (2001) Tsunami risk assessment in the Marquesas Islands (French Polynesia) through numerical modeling of generic far-field events. *Natural Hazards and Earth System Sciences* **1**, 233-242.

Hiscott, R.N., Middleton, G.V. (1980) Fabric of coarse deep-water sandstones Tourelle Formation, Quebec, Canada. *Journal of Sedimentary Petrology* **50**, 703-721.

Kain, C., Wassmer, P., Goff, J., Chagué-Goff, C., Gomez, C., Hart, D.E., Fierro, D., Jacobsen, G., Zawadzki, A. (2017) Determining flow patterns and emplacement dynamics from tsunami deposits with no visible sedimentary structure. *Earth Surface Processes and Landforms* **42**, 763-780.

Ketcham, R.A. (2005) Three-dimensional grain fabric measurements using high-resolution X-ray computed tomography. *Journal of Structural Geology* **27**, 1217-1228.

Larrue S., Chiron T. (2010) Les îles de Polynésie française face à l'aléa cyclonique. *VertigO* **10**(3): 1-14.

Laurent V., Varney P. (2014) *Historique des cyclones de Polynésie française de 1831 à 2010*. Météo-France, Papeete, 174 p.

Legland, D., Arganda-Carreras, I., Andrey, P. (2016) MorphoLibJ: integrated library and plugins for mathematical morphology with ImageJ. *Bioinformatics (Oxford Univ Press)* **32**(22): 3532-3534

Leibrandt, S., Le Pennec, J.L. (2015) Towards fast and routine analyses of volcanic ash morphometry for eruption surveillance applications. *Journal of Volcanology and Geothermal Research* **297**, 11-27.

Matsutomi, H., Okamoto, K., Harada, K. (2010) Inundation flow velocity of tsunami inland and its practical use. *Proceedings of the 32nd Conference on Coastal Engineering*, Shanghai, China, 2010.

Montaggioni L., Etienne S., Seard C. (2016) Récifs coralliens et paysages géomorphologiques des îles Marquises. In Galzin R., Duron S.-D., Meyer J.-Y. (eds), *Biodiversité terrestre et marine des îles Marquises, Polynésie française*. Société française d'Ichtyologie, Paris, 79-104.

Okal, E.A., Synolakis, C.E., Fryer, G.J., Heinrich, P., Borrero, J.C., Ruscher, C., Arcas, D., Guille, G., Rousseau, D. (2002) A field survey of the 1946 Aleutian tsunami in the far field. *Seismological Research Letters* **73**, 490-503.

Paris, R., Wassmer, P., Sartohadi, J., Lavigne, F., Barthomeuf, B., Desgages, É., Grancher, D., Baumert, P., Vautier, F., Brunstein, D., Gomez, C. (2009) Tsunamis as geomorphic crisis: lessons from the December 26, 2004 tsunami in Lhok Nga, west Banda Aceh (Sumatra, Indonesia). *Geomorphology* **104**, 59-72.

Paris, R., Wassmer, P., Lavigne, F., Belousov, A., Belousova, M., Iskandarsyah, Y., Benbakkar, M., Ontowirjo, B., Mazzoni, N. (2014) Coupling eruption and tsunami records: the Krakatau 1883 case-study, Indonesia. *Bulletin of Volcanology* **76**, 814.

Rees, A.I. (1965) The Use of Anisotropy of Magnetic Susceptibility in the Estimation of Sedimentary Fabric. *Sedimentology* **4**, 257-271.

Rees, A.I. (1968) The production of preferred orientation in a concentrated dispersion of elongated and flattened grains. *The Journal of Geology* **65**, 457-465.

Rees, A.I. (1983) Experiments on the production of transverse grain alignment in a sheared dispersion. *Sedimentology* 30 (3), 437-448.

Reymond, D., Hyvernaud, O., Okal, E.A. (2013) The 2010 and 2011 Tsunamis in French Polynesia: Operational Aspects and Field Surveys. *Pure and Applied Geophysics* **170**, 1169-1187.

Rusnak, G.A. (1957) Orientation of sand grains under conditions of unidirectional flow. *Journal of Geology* **65**, 384-409.

Sander, B. (1930) *Gefügekunde der Gesteine mit besonderer Berücksichtigung der Tektonite*. Part 1. Springer, Berlin, Vienna, 352 pp.

Schindelé, F., Hébert, H., Reymond, D., Sladen, A. (2006) L'aléa tsunami en Polynésie française : synthèse des observations et des mesures. *C.R. Geosciences* **338**, 1133-1140.

Schindelin, J., Arganda-Carreras, I., Frise, E. et al. (2012) Fiji: an open-source platform for biological-image analysis. *Nature Methods* **9,** 676-682.

Schneider, J.-L., Chagué-Goff, C., Bouchez, J.-L., Goff, J., Sugawara, D., Goto, K., Jaffe, B., Richmond, B. (2014) Using Magnetic Fabric to Reconstruct the Dynamics of Tsunami Deposition on the Sendai Plain, Japan — The 2011 Tohoku-Oki Tsunami. *Marine Geology* **358**, 89-106.

Shiki, T., Tachibana, T., Fujiwara, O., Goto, K., Nanayama, F., Yamazaki, T. (2008) Characteristic features of tsunamiites. In: Shiki, T., Tsuji, Y., Yamazaki, T., Minoura, K. (Eds.), Tsunamiites - Features and implications. Elsevier, 319-340.

Sladen, A., Hébert, H., Schindelé, F., Reymond, D. (2007) Evaluation of far-field tsunami hazard in French Polynesia based on historical data and numerical simulations. *Natural Hazards and Earth System Sciences* **7**, 195-206.

Sugawara, D., Goto, K., Jaffe, B.E. (2014) Numerical models of tsunami sediment transport – current understanding and future directions. *Marine Geology* **352**, 295-320.

Taira, A., Lienert, B.R. (1979) The comparative reliability of magnetic, photometric and microscopic methods of determining the orientations of sedimentary grains. *Journal of Sedimentary Petrology* **49**, 759-772.

Ulvrova, M., Paris, R., Nomikou, P., Kelfoun, K., Leibrandt, S., Tappin, D.R., McCoy, F.W. (2016) Source of the tsunami generated by the 1650 AD eruption of Kolumbo submarine volcano (Aegean Sea, Greece). *Journal of Volcanology and Geothermal Research* **321**, 125-139.

Wassmer, P., Schneider, J.-L., Fonfrège, A.V., Lavigne, F., Paris, R., Gomez, C. (2010) Use of anisotropy of magnetic susceptibility (AMS) in the study of tsunami deposits: Application to the 2004 deposits on the eastern coast of Banda Aceh, North Sumatra, Indonesia. *Marine Geology* **275**, 255-272.

FIGURE CAPTIONS

Fig. 1. Marquesas Islands (French Polynesia) and study sites. (A) Main historical earthquake sources for tsunamis affecting the Marquesas Islands. (B) Map of the archipelago. (C) Study sites in Nuku Hiva Island. (D) Study sites in Hiva Oa and Tahuata islands. Black dots indicate sites where tsunami deposits were sampled for X-ray tomography (XRT).

Fig. 2. Field evidence of tsunami in the Marquesas Islands. (A) Erosional scars in sand ridges, driftwood at 9 m a.s.l., and a 12-cm-thick sandy laminated deposit overlying a soil at Haatuatua Bay (Nuku Hiva Island, June 2012). (B) Coral boulders scattered along the river banks near Hooumi (Nuku Hiva Island, June 2012); a-axis of the largest boulder on the right measures 1.7 m. (C) Washover fan of pebbles and boulders attached to an old dune up to 36 m a.s.l. at Hanateio (Tahuata Island, June 2012). (D) The washover fan is a clast-supported conglomerate with a bimodal composition of corals and basaltic rocks. Note the presence of abundant driftwood.

Fig. 3. Evolution of sand ridges and washover fans in Haatuatua Bay (Nuku Hiva Island) between June 2005 and April 2013 (DigitalGlobe imaging provided by Google Earth©). Erosion of the lower sand ridge and progression of the washover fans inland at altitudes up to 15 m a.s.l. is probably due to the impact of the 2010 (Chile) and/or 2011 (Japan) tsunamis.

Fig. 4. Location of the sampling sites at Hooumi (southern coast of Nuku Hiva Island) and Tahauku (southern coast of Hiva Oa Island), and observed tsunami runups since 1946 (Schindelé et al., 2006; Reymond et al., 2013).

Fig. 5. Tahauku trench. (A) Shore-parallel section. Numbered circles and white squares correspond to bulk samples and anisotropy of magnetic susceptibility (AMS) samples, respectively. Two cores were sampled for X-ray tomography (TK03-A and TK03-B). (B) Shore-perpendicular section. (C) Results of AMS analyses: stereographic projection of the K_{max} (K1), K_{int} (K2) and K_{min} (K3) axes, and graphs of P (degree of anisotropy) versus bulk susceptibility and T (shape parameter of the ellipsoid, with $T > 0$ for oblate ellipsoids and $T < 0$ for prolate ellipsoids).

Fig. 6. Grain-size distributions of the different subunits observed on the Tahauku trench (shore-parallel section). Vertical and horizontal scale of the graphs represent the number of

particles (with n = total number of particles analysed) and the grain size (circle-equivalent diameter in µm), respectively. Black histogram is in linear scale, with the following sand size fractions: vf (very fine); m (medium); c (coarse); and vc (very coarse). Grey histogram is in logarithmic scale (upper x-axis labels in italic).

Fig. 7. Two-dimensional vertical slice, grain-size map and statistics (number of particles, maximum grain size and sorting index) obtained from X-ray tomography (XRT) at a vertical step of 2 mm down cores TK03-A and TK03-B (Tahauku). ND: no data (no reliable grain-size data could be obtained in clayey sediment such as mud lines and mud aggregates).

Fig. 8. Diagrams representing the sedimentary fabric characterised by X-ray tomography (XRT) at a vertical step of 2.5 mm down the TK03-B core. Four types of fabric are distinguished: (a) moderate-angle (15 to 35°); (b) bimodal low-angle (<15°); (c) moderate-angle with at least two different orientations; and (d) dispersed.

Fig. 9. Structure and vertical variations of grain size in core TK03-A. From left to right: original X-ray image of the core, recontrasted negative of the original image, and detailed views of a mudline and a lens of coarse sand intercalated in the laminated silty sand. Note the presence of tests of gastropods and abundant shell fragments, and laminae of heavy minerals.

Fig. 10. Three-dimensional view of a mudline at *ca* 22 cm depth in core TK03-A. White dotted lines correspond to the zonation of the mudline, illustrating variations of texture and composition.

Fig. 11. Post-tsunami deformation structures in the Tahauku trench. Subunit 1 corresponds to the 2011 Tohoku-oki tsunami (Japan), and subunits 2 to 6 relate to a previous tsunami (the 1946 Aleutian tsunami or 1960 Chile tsunami).

Fig. 12. Two-dimensional vertical slice, grain size map and statistics (number of particles, maximum grain size and sorting index) obtained from X-ray tomography (XRT) at a vertical step of 2 mm down cores Ho01-A and Ho01-B (Hooumi).

Fig. 13. Diagrams representing the sedimentary fabric characterised by X-ray tomography (XRT) at a vertical step of 2.5 mm down cores Ho01-A and Ho01-B. Types of fabric: (a) high-angle (up to 75°) fabric; (b) bimodal low-angle (<15°) fabric; (c) high-angle fabric with at least two different orientations; and (d) disperse fabric.

Fig. 14. (A) Anisotropy of the ellipsoids of grain orientation for different types of fabric (triangular diagram from Benn, 1994). S1: long axis of the ellipsoid (eigenvalue); S2: intermediate axis; S3: short axis. I: isotropy of the ellipsoid, with I = S3/S1. E: elongation of the ellipsoid, with E = 1-(S2/S1). The shape of the ellipsoid is represented at each end of the plot: isotropic (top), oblate (low left) and prolate (low right). (B) Elongation of the ellipsoid compared to its plunge.

Fig. 15. Grain-size distribution (in terms of sorting index and skewness) compared to the type of sedimentary fabric and its angle of plunge (Takauhu site). The angle of fabric is estimated from the plunge of the ellipsoid of orientation of the grains at a similar vertical step down the core.

Fig. 16. Grain-size distribution (in terms of sorting index and skewness) compared to the type of sedimentary fabric and its angle of plunge (Hooumi site). The angle of fabric is estimated from the plunge of the ellipsoid of orientation of the grains at a similar vertical step down the core.