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► 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

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

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14

15 **Associate Editor – Pedro Costa**

16 **Short Title – Fabric of tsunami deposits**

17

18 **ABSTRACT**

19 X-ray tomography is used to analyse the grain size and sedimentary fabric of two tsunami
20 deposits in the Marquesas Islands (French Polynesia, Pacific Ocean) which are particularly
21 exposed to trans-Pacific tsunamis. One site is located on the southern coast of Nuku Hiva
22 Island (Hooumi) and the other one is on the southern coast of Hiva Oa Island (Tahauku).
23 Results are compared with other techniques such as two-dimensional image analysis on bulk
24 samples (particle analyser) and anisotropy of magnetic susceptibility. The sedimentary fabric
25 is characterised through three-dimensional stacks of horizontal slices (following a vertical
26 step of 2.5 mm along the cores), while grain-size distribution is estimated from two-
27 dimensional vertical slices (following a step of 2 mm). Four types of fabric are distinguished:
28 (a) moderate to high angle (15 to 75°); (b) bimodal low-angle (<15°); (c) low to high angle

29 with at least two different orientations; and (d) dispersed fabric. The fabric geometry in a
30 tsunami deposit is not only controlled by the characteristics of the flow itself (current strength,
31 flow regime, etc.) but also sediment concentration, deposition rate and grain-size distribution.
32 There is a notable correlation between unimodal high-angle fabric – type (a) – and finely-
33 skewed grain-size distribution. The two tsunami deposits studied represent two different
34 scenarios of inundation. As demonstrated here, X-ray tomography is an essential method for
35 characterising past tsunamis from their deposits. The method can be applied to many other
36 types of sediments and sedimentary rocks.

37

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

40

41 **INTRODUCTION**

42 Despite considerable progress over the last decade, the interpretation of tsunami deposits still
43 suffers from a lack of both qualitative and quantitative criteria that would allow for a better
44 description of flow characteristics (e.g. Chagué-Goff et al., 2011; Goff et al., 2012; Sugawara
45 et al., 2014; Falvard & Paris, 2017; and references therein). Little attention has been paid to
46 the fabric of tsunami deposits. The fabric of a sedimentary formation corresponds to the
47 spatial arrangement of its grains (Sander, 1930) and its value in deducing depositional
48 processes has been emphasised by early workers (e.g. Dapples & Rominger, 1945; Rusnak,
49 1957; Hand, 1961; Rees, 1968). Anisotropy of magnetic susceptibility (AMS) is commonly
50 used to infer fabric patterns from the magnetic fabric (e.g. Rees, 1965; Taira & Lienert, 1979).
51 The technique has been applied to different types of sedimentary rocks and soft sediments,
52 including tsunami deposits (e.g. Wassmer et al., 2010; Cuven et al., 2013; Schneider et al.,
53 2014; Kain et al., 2017). Direct measurements of grain orientation on thin sections under the
54 microscope give more reliable results, but the geometry of the plane of section introduces
55 uncertainties and the technique is time-consuming (Taira & Lienert, 1979). As stated by Rees
56 (1965): “any rapid method of finding preferred grain orientation is, therefore, potentially of
57 great interest”.

58 The observed grain orientation in sediment reflects a final state of deposition and depends on
59 different parameters related to sediment (grain size, shape, density, sorting, etc.), bed

60 roughness and the flow itself (regime, sediment concentration, etc.). The primary fabric
61 corresponds to the grain preferred orientation during transport and is particularly well-
62 preserved in highly-concentrated flows that settle rapidly. When grains settle more slowly as
63 suspension fallout, they might be reoriented by rolling or sliding near the bed (Gupta et al.,
64 1987). Thus, the observed fabric does not always reflect the primary fabric. X-ray
65 tomography (XRT) provides a unique opportunity to characterise the three-dimensional
66 structure and texture of rocks and sediments, as demonstrated by its recent application to
67 tsunami deposits (Falvard & Paris, 2017, Falvard et al., 2018). This study characterises in
68 detail the vertical variations of grain size and clast fabric of tsunami deposits in the Marquesas
69 Islands (French Polynesia) using 2D and 3D analyses at the grain-scale.

70

71 **TSUNAMIS IN THE MARQUESAS ISLANDS**

72 The Marquesas Islands are located in French Polynesia (South Pacific Ocean) *ca* 1400 km
73 north-east of Tahiti and *ca* 4700 km from the nearest continent (Fig. 1). Over the past 26 kyr,
74 four successive phases of coral reef growth were interrupted by periods of sea-level rise and
75 reef drowning and thus the reefal shelf around the islands is poorly developed (Cabioch et al.,
76 2008; Montaggioni et al., 2016). The youngest reef terrace, dated 9 to 9.6 ka, is now at 60 to
77 55 m water depth on the foreslope of the islands. Reef building has stopped over the past 9 ka.
78 The largest islands have a shield-volcano morphology dissected by deep valleys that exit to
79 the sea as narrow open bays. The coastline of the Marquesas Islands is dominated by rocky
80 coasts with plunging cliffs or fringing shore platforms, whereas beaches and dunes are found
81 at the mouth of the river valleys and embayments.

82 Due to its central position in the Pacific Ocean, the archipelago is particularly exposed to
83 trans-Pacific tsunamis caused by earthquakes in Japan (2011), Kamchatka (1952), the
84 Aleutian (1946 and 1957), Alaska (1964), Peru (1868, 1996 and 2001) and Chile (1837, 1877,
85 1922, 1960 and 2010). Since the narrow bays are not protected by outer reefs, their
86 morphology is prone to tsunami amplification (Hébert et al., 2001). Tsunamis are part of the
87 Marquesian culture and the local expression ‘tai toko’ refers to catastrophic wave events
88 (Candelot, 1996). The oldest tsunami reported in the area dates back to 1806 (Candelot,
89 1996), and since 1837 there have been 17 reported tsunamis, seven of them with wave runups
90 exceeding 3 m (Schindel  et al., 2006; Sladen et al., 2007; Reymond et al., 2013). The 1946
91 Aleutian tsunami impacted all of the islands, with runups up to 18 m in the valleys (Schindel 

92 et al., 2006). No tropical cyclone has been ever recorded in the Marquesas Islands
93 Archipelago since the onset of meteorological observations in 1831. This is explained by the
94 geographical proximity of the equator inhibiting the organisation of convective clouds in
95 spiral bands (Larrue & Chiron, 2010; Laurent & Varney, 2014).

96 Tsunamis have left their mark on the coastal landscapes of the Marquesas Islands. During a
97 field survey in June 2012 the present authors noted numerous traces of sediments, driftwood
98 and erosion by extreme sea waves at altitudes up to 36 m above sea level (a.s.l.) (Fig. 2: coral
99 conglomerate at Hanateio, eastern coast of Tahuata Island). Coral boulders in the valleys (for
100 example, Hooumi in Nuku Hiva and Hanamenu in Hiva Oa) represent another compelling line
101 of evidence for tsunami inundation since there are no elevated reefs in the Marquesas.
102 Trenches made in low-energy morpho-sedimentary systems revealed fine-grained (mud to
103 sand) deposits fulfilling the typical trench-scale criteria of tsunami deposits (e.g. Shiki et al.,
104 2008; Goff et al., 2012). The main sedimentary facies observed are laminated sands in a
105 discontinuous contact overlying soil or lagoonal muds that are reworked as rip-up clasts and
106 mud lines. Some of the sedimentary successions observed have recorded several tsunamis (for
107 example, Haatuatua in Niku Hiva and Taipivei in Hiva Oa), including the 2011 Japan tsunami
108 deposits that were still well-preserved in June 2012. Satellite imagery of Haatuatua Bay
109 (eastern coast of Nuku Hiva) before and after the 2010 and 2011 tsunamis illustrates the
110 morphological imprint of recent tsunamis on coastal landscapes (Fig. 3). A comparison
111 between images from June 2005 and April 2013 shows erosion of the lower sand ridge,
112 driftwood deposition up to 9 m a.s.l. (Fig. 2) and progression of the sand washover fans inland
113 at altitudes up to 15 m a.s.l. (Fig. 3). There are no runup estimates available for the eastern
114 coast of Nuku Hiva, but Reymond et al. (2013) reported maximum runups of 3.8 m and 4.5 m
115 for the 2010 and 2011 tsunamis, respectively, on the southern coast.

116

117 **SAMPLING SITES AND METHODS**

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

124 1960 tsunamis were particularly high in Tahauku, with runups of 14 m and 12 m, respectively
125 (Schindel  et al., 2006).

126 Hooumi is located at the end of a funnel-shaped branch of the Baie du Contr leur (Fig. 4A).
127 There is no river outlet, and a small lagoon has formed behind the sandy beach. The sampling
128 site is a low altitude (<2 m a.s.l.) hand dug trench on the western side of the lagoon, 210 m
129 from the shoreline. Tahauku is another example of a funnel-shaped bay located east of Atuona
130 village (Fig. 4B). The site is particularly exposed to tsunami wave amplification (H bert et al.,
131 2001). A large trench was dug mechanically between the lagoon and the river outlet. Note that
132 the lagoon that was still visible on the November 2004 satellite imagery (Google Earth ) has
133 now disappeared due to successive sediment inputs from anthropic activities and tsunamis.

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

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

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

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

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

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

187

188 **RESULTS**

189

190 **Tahauku trench**

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

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

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

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

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

252

253 **Hooumi trench**

254 At Hooumi, the 2010 and 2011 tsunamis deposited fine patches of sand on the ground and
255 there is no notable sedimentary unit related to these two events in the local stratigraphy.
256 However, coral boulders along the river (Fig. 2B) and a massive sand unit overlying soil (Fig.
257 12) attest to deposition from at least one larger-magnitude tsunami. There is almost no
258 evidence of pedogenesis on top of this tsunami sand, suggesting that it corresponds to a recent
259 event. The 1946 tsunami is a candidate but its runup at Hooumi was similar to the 2010 and
260 2011 runups (<3 m; Schindel  et al., 2006).

261 The tsunami deposit is up to 40 cm thick (Fig. 12). Planar to oblique crude lamination is
262 visible over its entire thickness. The thinnest laminae are enriched in silt-sized material.
263 Pebbles and roots at the base (43 to 32 cm depth) and in the central part of the deposit (23 to
264 18 cm depth) introduced gaps in the XRT sampling. However, the two cores retrieved (Ho01-
265 A and Ho01-B) provide a high-resolution characterisation of grain size and fabric over two
266 intervals of 10 cm (Figs 12 and 13). Subtle vertical variations of grain size and sorting are
267 detected. Maximum grain size typically ranges between 0.4 mm and 0.6 mm, with three peaks
268 higher than 0.8 mm. Sediment is poorly sorted, especially at the base of the two cores. There
269 is no vertical grading except for a slight normal grading at the base of core Ho01-A (Fig. 12).

270 As in Tahauku, four types of clast fabric are distinguished (Fig. 13): (a) high-angle (25 to 75°)
271 fabric; (b) bimodal low-angle (<15°) fabric (two orientations with opposite angles); (c) low to
272 high angle fabric with at least two orientations; and (d) dispersed fabric. From base to top,
273 different trends of fabric are identified. The lower part of Ho01-B (33 to 30 cm depth) is
274 poorly organised (type-d fabric), except at the level of a silty lamina (type-b fabric weakly
275 oriented NNE or SSW). The lamina itself has a type-b fabric dominantly oriented NNE. From
276 30.0 to 26.5 cm depth, the data here record a progressive reversal from high-angle (type a)
277 fabric oriented north-east (i.e. dipping towards the south-west) to bimodal high-angle fabric
278 (type c), and finally high-angle fabric oriented SSW. After a short interval of disperse fabric
279 (type d), clasts are weakly inclined (type b) with north-west or south-east orientations (25.0 to
280 23.5 cm depth). Core Ho01-A (Fig. 13) starts with a phase of poor organisation associated
281 with normal grading. The sediment then adopts a clear high-angle fabric (type a) oriented
282 south-east to SSW (i.e. rotation of the plunge from NNW to NNE between 16.5 cm and 14.5

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

285

286 **DISCUSSION**

287

288 **Types of sedimentary fabric**

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

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

305 (ii) *Type-b fabric* is characterised by a low inclination of the grains (<15°) following two
306 opposite orientations. Thus, the direction of the current cannot be determined if it is assumed
307 that the fabric is parallel to the flow direction. At Tahauku, the type-b fabric is oriented
308 parallel to the inferred flow direction (oriented south-west/north-east), except in a very short
309 interval of flow-transverse fabric (south-east/north-west orientation at 38.5 cm depth on Fig.
310 8). The type-b fabric at Hooumi is parallel or slightly oblique to the flow (Fig. 13). Type-a and
311 type-b fabrics have similar degrees of anisotropy and elongation of the ellipsoid of grain

312 orientation (as defined by Benn, 1994) but they are different in terms of angle of fabric (cf.
313 plunge on fig. 14).

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

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

328

329 **Influence of the grain-size distribution on sedimentary fabric**

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

335 High concentration and rapid deposition of sediment can even hinder the development of an
336 anisotropic fabric because of significant interaction between touching grains and a lack of
337 space for spatial organisation (Hiscott & Middleton, 1980; Falvard & Paris, 2017). Schneider
338 et al. (2014) suggested that the primary fabric is better developed where fine-grained particles
339 (silts and clays) are mixed with sands. The relationship between the preservation of a primary
340 fabric and a finely-skewed grain-size distribution is particularly well-illustrated in the case of
341 Tahauku (Fig. 15), where sand is mixed with finer sediments from a lagoon. In the lower part
342 of core TK03-B, the onset of a type-a fabric with angles up to 35° is related to increased

343 coarse sand fraction and high values of skewness. This is concordant with the observations of
344 Capaccioni & Sarocchi (1996) who used XRT to characterise the vertical variations of the
345 fabric of an ignimbrite. The degree of preferred orientation of the elongated grains of the
346 ignimbrite is correlated with the percentage of matrix. At Hooumi, vertical variations of grain-
347 size distribution are less pronounced (Fig. 12), but two of the three major peaks of skewness
348 are found in sediments with a type-a fabric (Fig. 16). Thus, the development of type-a fabric
349 in a tsunami deposit is probably controlled by interactions between medium to coarse sand
350 and fine-grained fractions (silts, clays) and not only by the characteristics of the flow itself
351 (current strength, flow regime, etc.).

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

357

358 **Flow-parallel versus flow-transverse fabric**

359 The sedimentary fabric observed in the two tsunami deposits is oriented either parallel or
360 oblique to the inferred flow direction. Studies on the magnetic fabric of tsunami deposits
361 inferred from AMS reported both flow-parallel and flow-transverse orientations (Wassmer et
362 al., 2010; Paris et al., 2014; Schneider et al., 2014; Falvard & Paris, 2017). Falvard & Paris
363 (2017) combined AMS and XRT and found dominant low-angle flow-transverse fabrics in a
364 tsunami deposit. However, the quality of the scans both in terms of resolution and contrast did
365 not allow characterisation of the small-scale vertical variations of fabric.

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

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

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

389 The onset of flow-oblique fabric indicates a reduction of the bed shear stress and a re-
390 orientation of the grains by rolling or sliding near the bed (Gupta et al., 1987). In the data
391 herein, the ellipsoids of flow-parallel and flow-oblique fabrics are not significantly different
392 in terms of angle of fabric, isotropy and elongation. The influence of parameters such as
393 sediment concentration, grain size or flow regime on the production of fabric has been tested
394 in experiments on sheared dispersions of sand. Allen (1984) suggested that the vertical
395 variability of fabric reflects variations of flow regime. Poorly-sorted sands deposited in the
396 lower plane-bed phase show flow-parallel orientation patterns for the finer grains (<0.7 mm),
397 and both flow-parallel and flow-transverse orientations for the coarser grains (>0.7 mm). Rees
398 (1983) found that the flow-parallel fabric is preserved at low (1 to 2%) and high-sediment
399 concentration ($>11\%$), while the fabric becomes transverse for some intermediate
400 concentrations (3 to 8%). At intermediate concentration, the production of a flow-parallel
401 fabric is prevented by frequent 'grain to grain' collisions. At higher concentration, a reduction
402 of the distance between colliding grains creates transfers of angular momentum and does not
403 allow the development of a flow-oblique fabric (Rees, 1983), thus resulting in flow-parallel or
404 disperse fabric. The vertical variations of fabric observed in tsunami deposits could reflect
405 similar changes in sediment concentration (sediment pulses) and aggradation rate through

406 time. Transitions from flow-parallel to flow-oblique fabric could be related to the deceleration
407 of the flow and decrease of the sediment concentration, although local effects due to the
408 topography (for example, wave reflection in the narrow valleys and bed roughness) should not
409 be excluded.

410

411 **Variations of the angle of fabric**

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

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

439 Two different scenarios of inundation

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

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

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

469 At Hooumi, the 2 m high waves of the 1946 tsunami followed the Hooumi riverbed up to 660
470 m inland and deposited coral boulders up to 12 tons at 100 m from the shoreline (Okal et al.,
471 2002). The base of the boulders is buried in the tsunami deposit studied here, suggesting that
472 it is the same event, which is consistent with the absence of pedogenesis on top of the deposit.
473 The coarse-grained basal subunit including pebbles (not sampled for XRT) is overlain by a 20
474 to 30 cm thick succession of laminated sand. This crude lamination indicates periodical
475 variations of the aggradation rate due to successive sediment pulses that are associated with
476 subtle variations in grain size, sorting and fabric. As observed in Tahauku, the common
477 alternating type-b and type-d fabrics illustrate these variations of sediment concentration and
478 deposition rate. There are no erosive discontinuities between each new pulse, even during the
479 current reversals. A first reversal at 27 cm depth (Fig. 13) is characterised by type-a fabric
480 oriented north-east to type-a fabric oriented SSW, with transitional type-c fabric in between.
481 Another phase of backwash is identified in the upper part of the tsunami deposit, with type-a
482 fabric being notably directed seaward from 16.7 to 14.5 cm depth on core Ho01-A. The
483 association between high-angle type-a fabric and backwash currents at Hooumi is in favour of
484 a high deposition rate. The second backwash is preceded by a phase of suspension fallout, as
485 evidenced by normally-graded sediments with poorly-defined, flow-oblique fabric (17.5 to
486 18.5 cm depth). This is consistent with a decreasing concentration and deposition rate at the
487 end of the tsunami uprush. The fabric observed is not primary, as the grains settling down are
488 reoriented oblique to the flow by rolling near the bed.

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

502

503 **CONCLUSION**

504

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

519

520 **ACKNOWLEDGEMENTS**

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

528

529

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653

654 **FIGURE CAPTIONS**

655

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

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

668 **Fig. 3.** Evolution of sand ridges and washover fans in Haatuatua Bay (Nuku Hiva Island)
669 between June 2005 and April 2013 (DigitalGlobe imaging provided by Google Earth©).
670 Erosion of the lower sand ridge and progression of the washover fans inland at altitudes up to
671 15 m a.s.l. is probably due to the impact of the 2010 (Chile) and/or 2011 (Japan) tsunamis.

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

675 **Fig. 5.** Tahauku trench. (A) Shore-parallel section. Numbered circles and white squares
676 correspond to bulk samples and anisotropy of magnetic susceptibility (AMS) samples,
677 respectively. Two cores were sampled for X-ray tomography (TK03-A and TK03-B). (B)
678 Shore-perpendicular section. (C) Results of AMS analyses: stereographic projection of the
679 K_{\max} (K1), K_{int} (K2) and K_{\min} (K3) axes, and graphs of P (degree of anisotropy) versus bulk
680 susceptibility and T (shape parameter of the ellipsoid, with $T > 0$ for oblate ellipsoids and $T <$
681 0 for prolate ellipsoids).

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

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

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

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

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

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

703 **Fig. 11.** Post-tsunami deformation structures in the Tahauku trench. Subunit 1 corresponds to
704 the 2011 Tohoku-oki tsunami (Japan), and subunits 2 to 6 relate to a previous tsunami (the
705 1946 Aleutian tsunami or 1960 Chile tsunami).

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

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

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

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

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