

**1 X-RAY TOMOGRAPHY APPLIED TO TSUNAMI DEPOSITS:
2 OPTIMIZED IMAGE PROCESSING AND QUANTITATIVE ANALYSIS
3 OF PARTICLE SIZE, PARTICLE SHAPE, AND SEDIMENTARY
4 FABRIC IN 3D**

5

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18 **Keywords:** Tsunami deposit, X-ray computed tomography (X-CT), Particle size distribution, Particle shape
19 analysis, Sedimentary fabric, Image segmentation

20

21 ABSTRACT

22 The analysis of particle size, shape, size, and their spatial arrangement (i.e. fabric) in a sedimentary deposit plays
23 a significant role in their interpretation in terms of transport mechanism, flow conditions, and sediment source.

24 The present work focuses on the use of X-ray computed tomography (X-CT) to analyze tsunami deposits (core

25 samples), as examples of complex sedimentary assemblages. A workflow of image processing is proposed to
26 measure 3D parameters of particle size, shape, and orientation using two different software packages (Fiji-
27 ImageJ, and IPSDK) and two different methods of image segmentation. The semi-automated method provides
28 better segmentation quality of the tsunami deposit, as compared with the poor performance of fully-automated
29 image segmentation. We also provide some clues to reduce the computational time. This workflow is applied to
30 two examples of tsunami deposits on the coasts of the Algarve (1755 Lisbon tsunami, southern Portugal).
31 Optimized processing of X-CT images gives access to detailed vertical variations of grain size, grain shape, and
32 componentry (clayey matrix, silicates, and carbonates, including marine bioclasts), as well as information on
33 flow directions inferred from the sedimentary fabric in 3D. High-resolution analysis of the bedforms and vertical
34 grain size grading allows determining the flow conditions during the inundation phase of the tsunami.

35

36 1. Introduction

37

38 Since its early development in the 1970s (Hounsfield, 1973), X-ray computed tomography
39 (X-CT) imaging has been extensively used in the field of medical and biological sciences.
40 Being a non-destructive technique, X-CT characterization provides a three-dimensional
41 analysis of any complex object, which eliminates the conditional error that arises with two-
42 dimensional image processing. In earlier days, Flannery et al. (1987) demonstrated the
43 applicability of X-CT to glass beads, sandstone, and coal samples. Since the 1990s X-CT has
44 also increasingly used in Earth Sciences, especially for the structural and textural
45 characterization of rocks and sediments (Duliu; 1999; Mees et al., 2003; Cnudde and Boone,
46 2013). In sedimentology, X-CT was applied to marine sediments (Renter, 1989; Orsi et al.,
47 1994; Boespflug et al., 1995; Reilly et al., 2017; Yan et al., 2021) and more specifically to
48 turbidites (Goldfinger et al., 2012; Van Daele et al., 2014), but also on lake sediments (Flisch
49 and Becker, 2003), glaciogenic sediments (Tarpsee et al., 2011), and glaciolacustrine varves
50 (Bendle et al., 2015). Its application to high-energy event deposits such as storm and tsunami

51 deposits is quite recent (Cuven et al., 2013; May et al., 2016; Falvard and Paris, 2017; Falvard
52 et al., 2018; Paris et al., 2020; Biguenet et al., 2022).

53 X-CT offers new perspectives on the study of sedimentary deposits, especially on the links
54 between depositional processes, micro-scale structures (discontinuities, faulting, thin subunits,
55 etc.), bedforms (e.g., crude lamination), and texture of the sediment (grain size distribution,
56 grain shape, and sedimentary fabric). Despite recent advances in the processing of X-CT
57 volumetric datasets (e.g. Andrä et al., 2013; Müter et al., 2012; Reyes et al., 2017), works
58 focusing on a quantitative analysis of large-volume ($x \text{ cm}^3$) X-CT datasets of geological
59 samples are lacking.

60 The present study uses absorption-contrast mode X-ray computed tomography (X-CT) to
61 propose an accurate and robust image processing workflow that is suitable for any kind of
62 sedimentary deposit. To achieve that goal, X-CT analyses are performed on tsunami deposits,
63 which represent a challenging case-study because of their complex structure and texture.
64 Indeed, a tsunami deposit typically consists of particles of different sizes (from gravel to clay)
65 and types (silicates, bioclasts, wood, etc.) in a discontinuous fine-grained matrix (typically
66 clay-to-silt sized). The event deposit is often internally organized in subunits and laminated,
67 with erosive contact at the base, and sharp or erosive contacts between each subunit. This
68 spatial organization is combined with vertical variations of the grain size (e.g. Chagué-Goff et
69 al., 2011; Goff et al., 2012; Engel et al., 2021, and references therein). The workflow
70 presented here is focused on the optimization of image segmentation, allowing a reliable
71 quantitative analysis of particle size, particle shape, and particle orientation in 3D.

72

73 **2. Material and Methods**

74

75 2.1. Tsunami deposit sampling

76 Sediment core samples were collected in carbon tubes on two sites on the southern Algarve
77 coast of Portugal (Martinhal and Boca do Rio, Fig. 1), where deposits formed by the 1755
78 C.E. Lisbon tsunami are preserved in the coastal stratigraphy (e.g., Dawson et al., 1995;
79 Hindson and Andrade, 1999; Hindson et al., 1999; Kortekaas et Dawson, 2007; Cunha et al.,
80 2010; Costa et al., 2012a,b; Font et al., 2013, Vigliotti et al., 2019). The tubes are made up of
81 carbon fibers, which are almost transparent to X-rays, with a maximum length of 100 mm, an
82 outer diameter of 20 mm, and a wall thickness of 1 mm. After the sampling, the core sample
83 is stored under cold-stable conditions. In theory, X-CT can be used over any shape and size of
84 samples, but better results are obtained with tubular or cylindrical samples (Falvard and Paris,
85 2017; Ketcham and Carlson, 2001).

86 At Martinhal, the trench prepared for sampling is located ~250 m from the shoreline (Fig. 1).
87 The lowland is occupied by salt marsh vegetation and it is separated from the sea by a sand
88 barrier consisting of dunes and a beach. The 1755 C.E. tsunami deposit is made of silicate
89 particles (quartz, feldspars), lithogenic carbonates (calcite), biogenic carbonates (marine
90 bioclasts such as abundant bivalve shells, as well as gastropods, foraminifera, and ostracods),
91 mud aggregates, and rip-up clasts from the underlying brown estuarine mud (Hindson et al.,
92 1999; Costa et al., 2012a). The matrix between particles is discontinuous, forming either a
93 simple coating around individual particles or a wider-developed gangue including aggregated
94 clasts. At the sampling location, the deposit has a total thickness of 20 cm and displays
95 different subunits. Elsewhere its thickness varies from a few centimetres to 50 cm. The 10
96 cm-long core sampled a laminated fine-grained subunit at a depth of 60-70 cm below the
97 surface, just above the basal coarse-sand subunit (Fig. 2), which rests over an erosional
98 contact with the underlying mud.

99 The second site, Boca do Rio, is a flat-floored, sediment-infilled valley bounded by steep
100 slopes (Fig. 1). At the coast, a pebble beach covered by a thin veneer of sand and a rock spur
101 together form a barrier that limits inundation by storm surge (Dawson et al., 1995). The valley
102 is periodically impacted by river flooding leaving overflow silty sediment. The sampling site
103 is located in the middle of the valley at 320 m from the shoreline. The 1755 C.E. tsunami
104 deposit is a massive sand-to-gravel unit sandwiched within clayey silt sediments, with a lower
105 erosional contact. The tsunami unit is laterally variable in terms of structure, thickness, and
106 grain size (Hindson and Andrade, 1999). The event deposit contains gravel to boulder-size
107 limestone, occasional sandstone clasts, rip-up clasts of mud entrained from the soft estuarine
108 bottom, and abundant foraminifera, ostracods, and marine shells (Dawson et al., 1995;
109 Hindson et al., 1999). The 17 cm-long core sample (Fig. 2) covers only the upper part of the
110 tsunami deposit, corresponding to subunit B2 in Hindson and Andrade (1999), and 3.5 cm of
111 clayey silt sediment on top (subunit B1 in Hindson and Andrade, 1999). The other subunits
112 within the tsunami deposit were not suitable (too coarse) for our sampling technique.

113

114 2.2. X-ray computed tomography

115 The raw images were obtained at the Laboratoire 3SR, Grenoble, France, using RX-Solutions,
116 X-ray equipment consisting of a micro-focus X-ray generator, a flat panel detector, and a
117 rotating sample holder (Fig. 2). The X-ray source emits a polychromatic (i.e., photons with a
118 broad spectrum of energies) cone-shaped beam that interacts with the sample placed over a
119 rotating turntable. A flat panel detector detects the photons that have passed through the
120 sample as a two-dimensional projection of X-ray attenuation (which is closely related to the
121 density of the material) of the whole scanned volume at a certain orientation. Different
122 minerals with close values of density (e.g., quartz and feldspars) will have similar contrast
123 and they shall provide similar grey values during image analysis. High-density minerals (e.g.,

124 heavy minerals) and low-density materials (e.g., soil, wood) will respectively show light and
125 dark grey values.

126 The acquisitions were performed in a classical setup with a rotating sample (360°) and static
127 source and detector. The optimum scan settings for the specimens were determined at 100 kV
128 and 100 μ A, with 1 s exposure time per frame. The total acquisition scan was about 8 hours.
129 The tomographic projections were reconstructed with a filtered back-projection algorithm
130 resulting in tomograms with a pixel resolution of 8 μ m. This resolution is sufficient to
131 distinguish individual particles from the matrix and each other. The complex nature of a
132 tsunami deposit both in terms of composition and structure requires a relatively high
133 resolution to separate and characterize the different phases, and to characterize fine-grained
134 particles up to the silt size fraction (Figs. 3 and 4). The reconstructions were performed with
135 X-Act commercial software (RX-Solutions). Reconstructed data consists of a stack of 16-bit
136 Tiff image files representing a total number of 9868 and 12981 cross-sections along the core
137 (vertical slices from top to base), respectively for core MA-01 and core BR-01. The
138 distribution of the grey-scale values provides a first-order idea of the different phases of the
139 sample (Fig. 3). The deposit analyzed here consists of four different phases characterized by
140 different degrees of X-ray attenuation: particles of silicates (quartz, feldspars), particles of
141 carbonates (marine bioclasts such as shell fragments and foraminifers, but also lithogenic
142 carbonates such as calcite), clayey matrix (mud clasts, mud aggregates, interstitial mud), and
143 air (pores).

144

145 2.3. Image processing

146 For this study, we selected two software packages for conducting 3D image processing,
147 filtering, particle segmentation, and quantitative analysis: the free and open-source Fiji
148 distribution of ImageJ (Schindelin et al., 2012), and the commercial IPSDK (Image

149 Processing Software development Kit) provided by Reactiv'IP company (Reactiv'IP, 2020).
150 Fiji includes a variety of advanced image filtering options or segmentation modules that are
151 required for this work. IPSDK also offers a comprehensive and optimized range of 2D and 3D
152 image processing features and open-source code editing capabilities. It is available both in C
153 ++ and Python. For the present work, IPSDK was customized to meet specific challenges
154 related to image processing of complex granular material such as the sedimentary deposits
155 addressed herein. The following system configuration was used for performing the image
156 processing: Intel® Xeon® Gold 5218R CPU @2.10 GHz, 2 Sockets, 40 cores and 80 logical
157 processors, 128GB RAM, and 64-bit Windows 10 Pro OS.
158 Depending on the packing and sorting of the sediment, the degree of contrast between the
159 different phases in terms of density, and the complexity of the grains (i.e. individual particles)
160 in terms of shape, different strategies of image filtering, binarization, and segmentation can be
161 considered, as explained below.

162

163 *2.3.1. Image filtering*

164 Post-processing started by cropping and scaling the stack of images. Reconstructed X-CT
165 images were then filtered using a variance-weighted anisotropic diffusion 3D filter (Perona
166 and Malik, 1990; Weickert, 1997) or a patch-based bilateral 3D filter (Shimodaira, 2013) to
167 uniformly reduce the effect of noise while preserving the particle edges as sharp as possible.
168 A good balance between noise reduction and conservation of details must be tentatively
169 found. The anisotropic diffusion filter has the advantage of removing noise from the images
170 while preserving the boundaries and enhancing the contrast between the particles. The
171 threshold value of diffusion steps was determined by a parametric study. Each voxel in the X-
172 CT image is diffused unless the difference in the intensity between the voxel and its six face-
173 centered neighboring voxels exceeds a given threshold value. The resulting anisotropic

174 diffusion filtered images are smoothed grey-scale images. Increasing the number of steps
175 produces a decrease in edge detection, thus affecting particle separation (Fig. 5).

176

177 2.3.2. *Image binarization*

178 The purpose of the binarization is to separate the different phases in the sediment. In the case
179 of an automated segmentation (Fig. 6), the image was binarized using the Otsu algorithm
180 (Otsu, 1979). The Otsu thresholding binarization technique may not work effectively if the
181 sample is heterogeneous and densely packed. The use of the Otsu algorithm on X-CT images
182 may produce over-detection of particle edges because of the partial volume effect, resulting in
183 interface voxels between the particles and pores of lower intensity (low gray values). This
184 partial volume effect can be avoided by using a manual, or local, thresholding method. For the
185 semi-automated approach (Fig. 6), a manual selection of the threshold proved to be a more
186 effective method.

187

188 2.3.3. *Image segmentation*

189 Image segmentation aims at partitioning the binary images into individual particles. Among
190 the different methods available (e.g. Guntoro et al., 2019; Khaire and Thakur, 2013), the
191 distance transform marker-based watershed method is commonly used in studying X-CT
192 images of complex granular porous media (Faessel and Jeulin, 2010). A distance map was
193 first acquired from the thresholded image using a conventional morphological watershed
194 method (Jain, 1989). The flooding-based watershed algorithm (Beucher and Lantuejoul,
195 1979) was then applied to the inverted distance map to define the boundaries of individual
196 particles – that is, to separate the particles from voids. Markers (or *seeds*) are pixels or groups
197 of pixels from which the individual particles “grow” as the flooding progresses. A common
198 choice for the markers is the local minima or maxima of the morphological gradient of the

199 image. The required marker was determined automatically by another algorithm termed an
200 extended minima or maxima operator. Over-segmentation of particles with significant
201 differences in shape and size was often observed, leading to more local minima on the
202 distance map (Fonseca et al., 2012). To mitigate such over-segmentation problems, we used
203 the “Dilate Local Extrema 2d/3d” algorithm of IPSDK, and the “Extended Minima or
204 Maxima 2d/3d” algorithm of the MorpholibJ library. MorphoLibJ is a collection of
205 mathematical morphology methods and plugins for Fiji, created at the INRA-IJPB Modeling
206 and Digital Imaging lab (Legland et al., 2016). Explicitly computing the seeds according to
207 the image distance map and then computing a seeded watershed segmentation allowed for an
208 easier control of image segmentation.

209 A detailed workflow of both the automated and semi-automated segmentation is provided in
210 Figures 7 and 8. The semi-automated segmentation was done using the morphological
211 segmentation tool of the MorphoLibJ library included with Fiji and using the Advanced
212 Morphology library included with IPSDK. The source codes are available as supplementary
213 material (Suppl. 1, 2, and 3).

214

215 *2.3.4. Quantitative analysis of the particles*

216 Particle (grain) size was inferred through the diameter of the equivalent sphere (d_{eqv}), i.e., the
217 sphere having the same volume as the volume of the particle ($V_{particle}$) that is calculated from
218 the volumetric X-CT data (triangular surface mesh). The particle diameter was thus calculated
219 as follows:

$$d_{eqv} = \sqrt[3]{\frac{6 \times V_{particle}}{\pi}}$$

220 Vertical variation of the grain size distribution along the core was plotted using the
221 “Grainstat” Python code (developed by Falvard and Paris, 2017). Grainstat calculates the

222 median particle size (d50), first and third-size quartiles (d25, d75), maximum particle size,
223 number of particles, kurtosis, skewness, and sorting coefficient at a sub-sampling step size
224 defined by the user. Particles with an equivalent diameter smaller than 10 voxels (~80 microns
225 large) were filtered and ignored in the quantitative analysis, thus focusing on size fractions
226 that were reliably rendered in 3D.

227 For the characterization of the shape of the particles, we calculated the sphericity index,
228 which is a shape descriptor commonly used to quantify the similarity of a given particle to a
229 perfect sphere (Wadell, 1933). The sphericity index, as defined by Wadell (1933) is close to 1
230 for a perfect spherical shape and tends towards 0 for complex or plane-shaped particles.
231 Sphericity was calculated as follows:

$$\text{Sphericity} = \frac{\pi^{\frac{1}{3}}(6V_{particle})^{\frac{2}{3}}}{A_{particle}}$$

232 where $V_{particle}$ is the volume of the particle, and $A_{particle}$ corresponds to its surface area.

233

234 2.3.5. 3D orientation of the particles

235 During the sampling, sediment cores were oriented with respect to the North. Segmented
236 images are analyzed to characterize the orientation of all individual particles using the *Blob3D*
237 program (Ketcham, 2005). The 3D orientation of each particle was inferred from the direction
238 cosine of the three axes of the particle and the calculation of the azimuthal and dip angles.
239 The azimuth of orientation (with values ranging from 0 to 359°) was measured clockwise
240 from the North. The dip angle (0-90°) corresponds to the angle above the horizontal plane.
241 This fabric data was then processed using *Stereo32* program (Copyright © Klaus Röller,
242 Claudia A. Trepmann, Institut für Geologie, Mineralogie und Geophysik, Ruhr Universität)
243 and plotted as stereographic projections (equal angle projection, lower hemisphere). The
244 geometry of the fabric at a given vertical step along the core was inferred from the parameters

245 of the ellipsoid drawn by the three orthogonal eigenvectors. These parameters include the
246 degree of anisotropy, elongation, azimuth, and plunge (i.e., dip of the ellipsoid). The vertical
247 step of analysis was determined based on image resolution, quality, and number of particles
248 (typically thousands or even tens of thousands of particles at each vertical step). Here a
249 vertical step of 2.5 mm was selected for initial analysis, but the data can be reprocessed with
250 larger steps, to facilitate viewing.

251

252 3. Results

253

254 3.1. Computation time

255 With the computing system configuration used for this study, segmentation of the entire stack
256 could not be handled by Fiji, whereas IPSDK could easily perform it. IPSDK significantly
257 reduced the computational time of the analysis as compared to the results provided by Fiji,
258 especially for 3D calculations (Table 1). This is due to the ability of IPSDK software to
259 parallelize functions, which allows significant acceleration the speed of image processing
260 (Kornilov et al., 2020). Its framework uses all available CPU resources provided by the
261 hardware by combining an intensive usage of multi-threading and Simple Instruction Multiple
262 Data (SIMD) instruction sets.

263

264 3.2. Phase distribution and vertical variations of composition

265 The tsunami deposits used in the present study are clast-supported, but the low porosity (~8%)
266 of the two samples indicates that a fine-grained matrix is present, which is confirmed by the
267 X-CT images (Figs. 9 & 10). The matrix has a clayey-silt size distribution and it is then
268 referred to as mud for simplicity. This matrix between coarser particles is discontinuous,

269 forming either a simple coating around individual particles or a wider-developed gangue
270 including aggregated clasts. The tsunami deposits are composed dominantly of subangular to
271 subrounded silicate grains (40-45 % of quartz and feldspars), mud (25-35% of muddy matrix,
272 mud clasts, and mud aggregates), lithogenic and biogenic carbonates (12 and 24% for BR-01
273 and MA-01 respectively, consisting of limestone and individual calcite grains, and fragments
274 of shells and foraminifera), and heavy minerals (less than 1%).

275 The distribution of silicate, carbonate clasts (including bioclasts), and muddy matrix in the
276 tsunami deposit, as well as particle size and shape, varies vertically from base to top of the
277 cores. In core MA-01 (Fig. 9), the lower part (4-7 cm depth from the top of the core) of the
278 deposit is particularly rich in carbonates (>20%), including marine bioclasts, whereas the
279 upper part has fewer carbonates (~10%) and more silicates (>45%) and more clayey matrix
280 (25-30%). The lower part (5-8 cm depth) of core BR-01 is characterized by strong variations
281 of both the porosity and the matrix (which are negatively correlated) due to alternating fine-
282 grained and coarse-grained lamina (Fig. 10). Then from 5 cm depth to the top of the deposit,
283 the proportion of mud decreases progressively. The thin fine-grained sublayers associated
284 with crude lamination have a high proportion of matrix (and consequently a low porosity).
285 These matrix-supported mud lines are also rich in small-sized marine bioclasts. On the
286 contrary, coarse-grained sublayers are clast-supported (with a higher porosity but lower mud
287 content compared to fine-grained sublayers), even if they locally incorporate mud aggregates.

288

289 3.3. Particle size analysis

290 Comparative tests on core MA-01 between the results obtained on the particle (grain) size
291 distribution with the two different methods of image segmentation (automated and semi-
292 automated), and the two different software packages (Fiji and IPSDK) are provided as
293 Supplementary material (Suppl. 4 and 5).

294 Particle size distribution of the MA-01 tsunami deposit sample ranges from fine to very
295 coarse sand, with no significant differences between the different methods tested (Suppl. 4).
296 The distribution is unimodal and poorly sorted, with a peak ranging from 100 μm to 300 μm
297 (depending on the stack or region of interest considered). The mean equivalent diameters
298 calculated using the semi-automated segmentation are consistently smaller than the ones
299 calculated using automated segmentation. Indeed, semi-automated segmentation slightly
300 overestimates the actual number of particles. This is mostly attributed to digital pixel noise
301 (adding small dots), which can be easily removed by applying a despeckle filter. On the other
302 hand, examination of the connected component labeled images produced with the automated
303 methods (Fig. 7) reveals that many artificial particles are created because the dilated minima
304 process often merges several small seeds, especially when particles have a complex shape.

305 Vertical variations of the equivalent particle size are roughly similar for all types of
306 segmentation methods (Suppl. 5), except that (a) the semi-automated method gives smaller
307 mean equivalent diameters (for the reasons mentioned above), and (b) Fiji gives larger mean
308 equivalent diameter values compared to IPSDK. The step size of 500 μm adopted here
309 renders all significant variations of grain size along the cores (Suppl. 6). The particle size
310 distribution of the lower half of core MA-01 is coarser and better sorted compared to its upper
311 half (Suppls. 4 & 5; Fig. 11), which displays more matrix and finer-grained mud-rich
312 sublayers (referred to as mud lines), resulting in stronger variations of particle size and sorting
313 (Fig. 11). Considering a larger step size of analysis (e.g. 5 or 10 mm), MA-01 appears slightly
314 normally-graded from 6 to 3.5 cm depth (Suppl. 6).

315 Analysis of the BR-01 core shows subtle vertical variations of grain size (Fig. 12). Overall,
316 the deposit is poorly sorted. The lower part of the core (5-8 cm depth) is characterized by
317 alternating laminae of clast-supported fine-to-medium sand and matrix-supported fine sand.
318 The base of the deposit (7-8 cm depth) is inversely graded, as seen both on the mean and

319 maximum grain size (Fig. 12). The upper part of the deposit (0-5 cm depth) is more
320 homogenous in terms of mean grain size and sorting, except peaks of maximum grain size
321 that are due to the presence of large fragments of bivalve shells.

322

323 3.4. Particle shape analysis

324 The different phases found in the tsunami deposit are characterized by different shapes. As an
325 example, marine bioclasts display more complex shapes and consequently a lower degree of
326 sphericity compared to silicate grains (Fig. 13). Particle sphericity distribution obtained using
327 IPSDK shows peak values ranging from 0.6 to 0.8 (often centered to 0.8), whereas Fiji gives
328 more flatten distributions, often bimodal, with peaks between 0.4 and 0.8 (Suppl. 7). The
329 segmentation method in Fiji generates a significant number of irrelevant artifacts with odd
330 shapes. In contrast, the distribution obtained with the IPSDK is much less noisy, because the
331 mesh approximating the particle shape is denser compared to Fiji, and thus provides a better
332 estimate of the shape. In Fiji, the mesh is not accurate enough, especially for very small (less
333 than a few hundred voxels in diameter), flat, and complex particles.

334 Vertical variations of the sphericity values along core MA-01 (Fig. 14) confirm that there is a
335 significant difference between the two softwares, but also between the two segmentation
336 methods. The difference between automated and semi-automated segmentation in terms of
337 sphericity distribution is due to the presence of complex particles such as bioclasts and mud
338 aggregates, or muddy matrix around particles, which cannot be removed easily with
339 automated segmentation, hence locally resulting in a bimodal sphericity distribution (Suppl.
340 7). Consequently, the automated segmentation technique seems inappropriate in the upper
341 half of core MA-01, which contains a higher proportion of matrix (Fig. 9). There is also a
342 clear relationship between the mean sphericity of the particles and the abundance of marine
343 shells in the sediment, as seen in the upper third of core MA-01 (Fig. 14).

344

345 3.5. Sedimentary fabric inferred from the 3D orientation of the particles

346 We can distinguish different types of sedimentary fabric on the stereograms (Figs. 15 and 16):
347 (a) an unimodal fabric with a single azimuth angle (i.e., direction) corresponding to a type-a
348 fabric according to Paris et al. (2020); (b) a bimodal fabric (type-b from Paris et al., 2020);
349 and a dispersed fabric (type-d from Paris et al., 2020). Most of the stereograms display type-b
350 and type-d fabrics, but type-a fabric locally appears in core MA-01, especially in the coarse
351 sand fraction (Fig. 15). The bimodality of type-b stereograms is not always symmetrical, thus
352 giving birth to transitional a-b fabrics. On both cores, the fabric is more dispersed in the very
353 fine and fine sand fractions, compared to the medium and coarse sands. The dip angle of the
354 fabric ranges between 5 and 20°, with a mean value of 12°.

355 As for the grain size and grain shape, the fabric shows vertical variations both in terms of
356 anisotropy and azimuth angle, especially in the medium and coarse sand fractions. In core
357 MA-01, the fabric seems better organized in the lower part of the deposit (4.5-7 cm depth in
358 Fig. 15), with bimodal type-b fabric oriented NW-SE to NNW-SSE (well recorded in the
359 medium sand fraction), turning to type-a fabric at 4.5-5 cm depth. In the middle part (1-4.5
360 cm depth), unimodal type-a or bimodal type-b fabrics are preserved in the very coarse sand
361 fraction, while dispersed fabric dominates the other fractions. At the very top of the deposit,
362 type-b fabric is oriented E-W (0-1 cm depth).

363 In core BR-01, the fabric is poorly organized (type-d), except for short intervals of type-a
364 fabric directed NW-NNW at 6.4 cm depth, type-b fabric oriented NW-SE at 3 cm depth, and
365 transitional a-b fabric oriented NW-SE to NNW-SSE at 0.5 cm depth, as recorded in the
366 medium sand fraction (Fig. 16). The results obtained in the coarse sand fraction of BR-01 are
367 not reliable, due to a limited number of particles (<50, compared to thousands of particles for
368 the other size fractions).

369

370 4. Discussion

371

372 4.1. Segmentation methods

373 Separating individual complex-shaped particles in a tsunami deposit in 3D is a major
374 challenge in terms of image processing. Marker-based distance transform watershed
375 segmentation is usually a very efficient algorithm that provides a satisfactory solution and
376 prevents over-segmentation (Beucher and Meyer, 2019), but the challenge itself is the
377 separation of individual particles. The automated segmentation process makes use of a 3D
378 distance transform of the binary image to create a distance map on which a 3D watershed
379 transformation is applied to separate the pore space into distinct particles. This is achieved by
380 identifying watershed basins around each local maxima of the distance transform, resulting in
381 one particle object associated with every local maxima. However, when particles have a rough
382 surface, the application of this technique can break the particles into many small objects due
383 to additional local maxima near the surface of small objects. The main limitation of this
384 partitioning method is the use of spherical structuring elements when identifying watershed
385 basins, which might not cope very well with tortuous interconnected particle clusters or
386 complex-shaped particles.

387 The semi-automated segmentation process uses a watershed transformation of the image
388 gradient (such as morphological or Gaussian gradient) constrained by markers (one marker
389 for each object and one for the background). In that case, the correctness of the segmentation
390 depends on the quality of the gradient and the relevance of the markers. Furthermore, to
391 obtain representative boundaries between particles, an appropriate choice of the threshold

392 value of the distance map could be a satisfactory solution to reveal boundaries between large
393 particles and the matrix.

394 In terms of particle size distribution, a great discrepancy is found between the automated and
395 semi-automated methods, both for Fiji and IPSDK. The semi-automated segmentation process
396 provides a better separation of particles from the matrix. The two methods provided similar
397 particle size distribution results when tested on the lower half of the MA-01 core (3-7 cm
398 depth), but great discrepancies were found when the methods were applied to the upper half
399 of the core (0-3 cm depth), which is enriched in matrix and mud aggregates. One can observe
400 several touching particles, which are not disconnected in the automated segmentation, while
401 every object is identified in the case of the semi-automated segmentation. Boundaries
402 between objects are often misplaced in the first case, while they are precisely reproduced in
403 the second case. Large particles with a complex shape (e.g. mud aggregates) are often
404 excluded or treated as voids. Indeed, a higher concentration of matrix prevents particle
405 segmentation, hence generating larger or missing objects, especially in the case of automated
406 segmentation.

407 One of the main advantages proposed by the semi-automated method is that it better
408 reproduces the convexity of complex-shaped objects. The identified seeds used in the
409 watershed-based methods presented here are derived from the extended maxima of the
410 distance map function. Hence, they tend to describe objects as a union of convex shapes.
411 Automated segmentation algorithm constrained with such markers tends to over-segment
412 concave objects. For instance, a concave-shaped particle is largely over-segmented with the
413 automated segmentation method (images a, b, and c in Fig. 17). Furthermore, two touching
414 particles whose union owns a single maxima in the distance map function are merged as a
415 single seed with automated segmentation method (image d on Fig. 17). As the semi-
416 automated method approach presented here exempts us to use standard markers, objects are

417 correctly segmented whatever their convexity, and even in the presence of a muddy matrix.
418 The comparative segmentation results show that the semi-automated segmentation technique
419 successfully overcomes major challenges posed by the large diversity and complexity of the
420 tsunami deposits studied here. Given the ability of the technique to deal with particles with a
421 complex morphology, it could be readily used to segment other kinds of complex granular
422 materials.

423

424 4.2. Influence of the segmentation method on the particle size distribution

425 There exists a difference in the level of agreement among particle size distribution
426 measurements estimated using different segmentation methods. The automated segmentation
427 method underestimates the smallest fractions and overestimates the number of complex-
428 shaped large particles (e.g., fragments of bivalve shells), especially in regions enriched in
429 muddy matrix and mud aggregates. In our case, the lack of phase contrast between individual
430 particles and the matrix aggravates this drawback. Therefore, the particle size distribution is
431 artificially skewed to the coarse side (Suppl. 4).

432 With semi-automated segmentation many small objects, which could not be distinguished
433 using automated segmentation, are preserved. The semi-automated segmentation process can
434 produce both (a) large-size seeds for large and complex particles, and (b) small-size seeds for
435 very fine particles. With the automated segmentation, the smallest particles are not detected
436 due to seeds or markers limitations. The semi-automated segmentation also makes use of
437 spherical structuring elements when performing watershed to produce watershed lines to
438 remove the unwanted matrix, while the automated segmentation methods cannot always
439 remove the matrix around the particles.

440

441 4.3. Influence of the segmentation method on the particle shape

442 Characterization of the particle shape is also influenced by the choice of the segmentation
443 method. Although particles are mostly sub-angular, some of the particles are far from being
444 perfect spheres (Fig. 13). The automated segmentation method often fails to accurately
445 reproduce complex-shaped particles, thus giving less reliable values of sphericity, compared
446 to the semi-automated method (Suppl. 7). The two methods are in agreement if there is a very
447 low proportion of matrix in the deposit, but as for the particle size, the results are less reliable
448 when the matrix is abundant, as well as complex-shaped particles (e.g., bioclasts). The lack of
449 agreement among the estimation of particle shape can thus be attributed to the way each
450 segmentation method handles interconnected particle clusters as well as matrix-supported
451 horizons or lamina. For the tsunami deposits studied here, only the methods based on semi-
452 automated segmentation produce consistent results on particle shape.

453

454 4.4. Implication for the interpretation of tsunami deposits at a microtextural scale

455 Tsunami deposits are complex because they result from the mixing of different sources of
456 sediments both from nearshore and onshore zones, thus including particles of different sizes
457 and shape, as well as varied lithologies. In terms of shape, the most challenging particles to
458 characterize in 3D are the marine bioclasts. Fragments of shells may be very thin and they
459 often have a high aspect ratio (e.g., bivalve shells). Corals and tests of gastropods and
460 foraminifers are characterized by complex geometries, making them particularly difficult to
461 segment in 3D. Another source of complexity may come from the lack of contrast between
462 the two phases that are in contact. For instance, some particles and the matrix around particles
463 may have a similar coefficient of attenuation of X-rays (e.g. silicate sand in a silicate mud).

464 Compared to the other techniques commonly used for the characterization of tsunami
465 deposits, X-ray tomography is far more than a 3D tool (Paris, 2020). Indeed, it gives access to

466 much information that is not always visible to the eye or using conventional techniques, such
467 as:

- 468 • a hidden or poorly-defined structure of the deposit (e.g., units apparently massive may
469 be structured in subunits, which may change the interpretation);
- 470 • poorly-defined bedforms (e.g. crude lamination whose identification is crucial in terms
471 of flow dynamics);
- 472 • structures related to bioturbation that may cast doubt on the detailed interpretation of
473 some parts of the deposit;
- 474 • small-size marine bioclasts whose identification confirms the marine nature of the
475 deposit, especially if coarse bioclasts are absent;
- 476 • the presence and proportion of a matrix in the sedimentary assemblage and its
477 significance in terms of flow dynamics and sediment sources;
- 478 • and the sedimentary fabric (i.e. the spatial arrangement of the particles in 3D), which
479 provides information on the flow dynamics, current orientation, and particle
480 concentration.

481 All these features should be described not only qualitatively but also quantitatively, which
482 requires an appropriate and efficient segmentation workflow (assuming that the scanning
483 parameters are already optimized). Once segmentation is achieved, image analysis provides
484 statistics and graphs on all particles or a single phase (e.g. bioclasts or heavy minerals).
485 Typical plots that can be produced include size metrics (mean, maximum size, sorting,
486 skewness, etc.), shape metrics (sphericity, convexity, etc.), phase distribution (e.g. silicate
487 clasts, matrix, bioclasts, etc.) plotted as a function of depth along the core. As an example,
488 optimized segmentation and quantitative analysis of the core sample provide an in-depth
489 characterization of the 1755 tsunami in Martinhal and Boca do Rio. First, X-ray imagery
490 confirms that at these sampling sites, the event-deposits are well-preserved and not

491 bioturbated. A macroscopic examination of the deposits would conclude that they are clast-
492 supported, but in fact, the deposits are not clast-supported all along the core. The proportion
493 of the matrix varies with depth (Figs. 9 and 10) and some mud-rich subunits are matrix-
494 supported (e.g., medium sand mixed with clayey silt at 6-7 cm depth on MA-01).

495

496 *4.4.1. Martinhal (MA-01)*

497 Two different parts can be distinguished in the MA-01 tsunami deposit. The lower part (3.5-7
498 cm depth) is quite homogenous in terms of composition, particle size, and particle shape
499 (Figs. 9 & 12). It is poorly sorted, with clast size ranging from silt to very coarse sand. The
500 upper part (0-3.5 cm depth) is slightly finer and better sorted. In terms of phase distribution,
501 the upper part has a higher proportion of silicates, but a lower proportion of carbonates
502 compared to the lower part (Fig. 9). Lower values of sphericity in the upper part of the
503 deposits (Suppl. 7) are consistent with a higher abundance of marine shells, compared to the
504 lower part (Fig. 14). There is a decorrelation between the proportion of carbonate and the
505 number of shells. Indeed, the carbonates are either lithogenic (calcite from the local Upper
506 Jurassic limestones) or biogenic (i.e. marine bioclasts), but the distinction between the two
507 types of carbonates cannot be inferred from the density itself (i.e. gray values in Fig. 9). In the
508 upper part of the deposit (0-3 cm depth), alternating fine and medium sand subunits create a
509 crude lamination. The fine sand subunits are enriched in marine bioclasts and clayey-silt
510 matrix, and they may correspond to a kind of poorly-defined mudlines, which is a common
511 feature in tsunami deposits (e.g., May et al., 2016; Falvard and Paris, 2017).

512 Kortekaas and Dawson (2007) described the Martinhal tsunami deposits as normally graded,
513 with up to 3-4 fining upward sequences, depending on the sites. An in-depth analysis of the
514 vertical variation of particle size from base to top of the deposit analyzed here shows no
515 progressive vertical grading over the entire sequence, although the lower part is indeed

516 coarser than the upper one (Fig 11). The normal grading detected between 3.5 and 6 cm depth
517 is very slight, with a mean grain size turning from 200 μm at 6 cm depth, to 170 μm at 3.5 cm
518 depth (Suppl. 6)., the overall trend of vertical grading of a tsunami deposit, which is often a
519 fining upward trend, is superimposed on subunit-scale variations of grading, whatever inverse
520 or normal, as highlighted by earlier studies using X-ray tomography on tsunami deposits (e.g.,
521 Falvard and Paris, 2017).

522 The sedimentary fabric of MA-01 is better organized in the lower part (4.5-7 cm depth in Fig.
523 15) compared to the upper part (0-4.5 cm depth). The type-b bimodal fabric recorded in the
524 medium and coarse sand fractions of the lower part is oriented NW-SE, which is consistent
525 with a flow coming from the SE after crossing a coastline that is oriented SW-NE (Fig. 1).
526 This fabric is thus parallel to the flow. In the upper part of the deposit, the fabric is rather
527 chaotic, dispersed in all the sand size fractions, except for type a/b fabric in the very coarse
528 sands (Fig. 15). Variations of the angle of fabric as recorded in the coarsest fractions may
529 indicate an effect of wave resonance in the lowland basin.

530

531 4.4.2. Boca do Rio (BR-01)

532 The core sample BR-01 analyzed here corresponds to the upper part of the tsunami deposit,
533 referred to as subunit B2 in Hindson and Andrade (1999), Font et al. (2013), and Vigliotti et
534 al. (2019). X-CT analysis provides additional details on the internal structure and grain size
535 variations of this specific subunit. First, the base of B2 (7-8 cm depth) displays a clear inverse
536 grading associated with an upward decrease of the sorting (Fig. 12). Although normal grading
537 is the dominant type of vertical grading (if any) found in tsunami deposits, inverse grading
538 has been often reported at the base of tsunami deposits or individual tsunami subunits (e.g.,
539 Paris et al., 2007; Choowong et al., 2008; Moore et al., 2011; Jaffe et al., 2012; Falvard and
540 Paris, 2017, Moreira et al., 2017).

541 X-CT analysis also demonstrates that the B2 subunit is not as massive and homogenous as
542 what can be seen at the trench scale. There are two distinct parts. The lower part (5-8 cm
543 depth) consists of alternating lamina of (a) clast-supported fine-to-medium sand, and (b)
544 matrix-supported mud-rich fine sand, giving the deposit a crudely-laminated texture. A
545 similar lamination associated with small-scale variations of grain size was also described on
546 other tsunami deposits, and interpreted as upper-plane beds formed by successive pulses of
547 sediment supply (Falvard and Paris, 2017; Paris et al., 2020). This laminated lower part is
548 characterized by a dispersed fabric (type-d), except for a very short interval of type-a fabric
549 directed NNE (at 6.4 cm depth in Fig. 16). This is concordant with the poorly-defined NE
550 flow direction inferred from the analysis of the anisotropy of magnetic susceptibility (AMS)
551 by Vigliotti et al. (2019). The dominant oblate shape of the ellipsoids of AMS (shape
552 parameter $T > 0$ in Vigliotti et al., 2019) is also in agreement with a dispersed fabric.

553 Disperse fabric continues up to 3.5 cm depth in the upper part of the deposit (Fig. 16). The
554 conditions to produce a dispersed fabric are still unclear, but this could correspond to a hyper-
555 concentrated flow in which the primary fabric could not be preserved at the time of deposition
556 (Rees, 1983), for reasons related to the depositional rate or the grain size distribution (Paris et
557 al., 2020). A low depositional rate associated with a lower sediment concentration allows for
558 more time for the grains to rearrange their orientation during settling, especially if there is no
559 matrix or fine-size fraction between the coarse grains.

560 In the massive upper part of the deposit (0-3.5 cm depth), the fabric is slightly better
561 organized, especially in the medium sand fraction, where the transitional a-b fabric indicates
562 an NW-SE to NNW-SSE orientation. This is concordant with the NNW-SSE orientation of
563 the valley. The slight asymmetry of the fabric towards the NW-NNW rather points to a flow
564 that is still directed landward.

565

566 4.5. Advantages and limitations of the proposed workflow

567 In sedimentology, most studies using X-CT images do not fully exploit their strong potential
568 because the analysis remains essentially qualitative. As an example, Reilly et al. (2017)
569 designed a user-friendly suite of Matlab tools (SedCT) to analyze X-CT images of sediment
570 cores. The density of the sediment is estimated from the attenuation coefficient expressed in
571 Hounsfield units. Similarly, Yan et al. (2021) developed a Matlab application (Core-CT)
572 allowing the user to identify boundaries of density contrast and to run 3D geometrical
573 measurements of these structural boundaries. The approach was applied to marine and lake
574 sediment cores, and coral cores.

575 Quantitative analysis of X-CT images at the grain scale remains quite rare. Cnudde et al.
576 (2011) used the Morpho+ software (Vlassenbroeck et al., 2007) to segment a sandstone
577 sample and to provide its grain size distribution (equivalent diameter in % volume), and the
578 sphericity distribution. They worked at two different resolutions: 7.4 μm on a partial volume
579 of 343 mm^3 (53103 grains analyzed), and 0.7 μm on a 0.57 mm^3 subsample (710 grains). In
580 comparison, we have here analyzed a volume of 23,000 mm^3 at a resolution of 8 μm , thus
581 providing shape and size statistics for ~40,000 grains. This ability to process a large volume
582 in a single piece is mainly linked to the optimization of calculation methods (Table 1).

583 However, the quality of the segmentation (and therefore the reliability of the results) depends
584 mostly on the workflow defined by the user. In some cases such as heterogeneous sediments
585 rich in bioclasts, this workflow can be complex. Kong and Fonseca (2017) used an adaptative
586 watershed method to segment a shell-rich sand, to improve the understanding of its
587 mechanical properties. Their method is quite close to the one we use for automatic
588 segmentation, the limits of which we have demonstrated above.

589 The quality of the semi-automatic segmentation method that we propose here makes it
590 possible to analyze any type of sediment at the grain scale. If the samples are spatially

591 oriented, the dynamics of transport and deposition can be understood through the analysis of
592 the sedimentary fabric. Van Daele et al. (2014) inferred the flow direction of turbidites from
593 the description of folds in slumps, climbing ripples, asymmetrical convolution, and imbricated
594 clasts in turbidites. However these features are not always visible at the core scale. Our
595 method makes it possible to study the sedimentary fabric at the grain scale and different
596 scales: whole core, regions of interest, subsections defined at a regular step, etc.
597 X-ray tomography should not be presented as a unique method replacing conventional
598 methods such as laser diffraction granulometry, or optical and electron microscopy. Previous
599 studies conducted by Falvard and Paris (2017) and Paris et al. (2020) have already carried out
600 comparisons between these different methods, thus proving their complementarity. Even if
601 the calculation times necessary for image segmentation are less and less limiting, X-CT does
602 not yet reach the resolution of a scanning electron microscope (e.g., for the identification of
603 small-size foraminifers and diatoms). Another limitation is that compared to a laser particle
604 size analyzer, the grain size distribution estimated by X-CT is limited by the resolution and
605 therefore by the scanned volume. To obtain a reliable total grain size distribution, several
606 scans will have to be carried out at different resolutions, the finest particle size fractions (e.g.,
607 silts) being taken into account only on small-volume subsamples.

608

609 5. Conclusions

610

611 Recent developments in X-CT open the possibility of imaging and characterizing geological
612 samples at a resolution that was unimaginable a couple of decades ago. The tsunami deposits
613 selected for this study are a case-studies of complex sedimentary deposits whose image
614 processing is particularly difficult and potentially time-consuming. The X-CT is a feasible
615 approach to characterize the structure and texture of sedimentary deposits, including multi-

616 phase deposits with complex-shaped particles such as tsunami deposits, storm deposits, or
617 turbidites. The semi-automated workflow of image segmentation proposed here appears to be
618 far more performant and reliable than a fully automated segmentation.

619 X-CT gives access to a level of detail hitherto unequaled on the internal structure, the vertical
620 variations of grain size, the distribution of marine bioclasts, and the sedimentary fabric as an
621 indicator of the flow direction in a tsunami deposit.

622 This study lays the groundwork for further studies focused on the practical development of
623 standardized image segmentation methodologies for sedimentary deposits and other complex
624 geological samples. With some modifications from one case to another, the method of
625 segmentation presented here applies to most of the sedimentary deposits or rocks. Further
626 studies could focus on improved segmentation between particles and a matrix with a similar
627 chemical composition (i.e. implying poor contrast between the particles and the matrix).

628

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637

638 **Data availability**

639 Name of the code: SegGeol.

640 Contact: raphael.paris@uca.fr

641 Code languages: Python (IPSDK), Java (Fiji).

642 Environment/software required: any Python environment (e.g. Spyder IDE, PyCharm) with

643 IPSDK installed, or Fiji-ImageJ (Java language).

644 The source codes are available as supplementary material.

645

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858

859 **FIGURE CAPTIONS**

860

861 Fig.1 – Location maps of the study areas on the southern Algarve coast of Portugal.

862

863 Fig. 2 – On the left: cross-sectional views of the 1755 C.E. Lisbon tsunami sampled in
864 Martinhal (MA-01 core) and Boca do Rio (BR-01 core). On the right: X-CT scan setup of a
865 tsunami sediment core at Laboratoire 3SR, Grenoble, France.

866

867 Fig. 3 - Typical workflow of X-CT image analysis. The distribution of grey values is used to
868 select threshold values for separating the four different classes: pores, mud (clayey matrix,
869 and mud clasts), silicates (quartz and feldspar particles), and carbonates (lithogenic carbonates
870 such as calcite, and biogenic carbonates such as marine shells and foraminifers).

871

872 Fig. 4 - Three-dimensional views of the MA-01 core of tsunami deposit, obtained from X-CT.
873 A: general view of the core (2 cm large, 10 cm long); B: closer-view on the upper part of the
874 core, showing crude lamination; C: closer-view of the lower part of the core, which is coarser-
875 grained compared to the upper part; D: matrix-supported clay-rich lamina; E: same as D, with
876 carbonate clasts in red, silicate clasts in orange-yellow, the clayey matrix in light blue, and
877 pores-void in dark blue; F: closer-view on the clast-supported, coarse-grained facies of the
878 lower part of the core, with abundant marine bioclasts (shell fragments, broken tests of
879 foraminifera).

880

881 Fig. 5 - Sensitivity analysis of the different steps used in the anisotropic diffusion filter.

882

883 Fig. 6 – Image segmentation workflows. Left: automated segmentation. Right: semi-
884 automated segmentation.

885

886 Fig. 7 - Automated segmentation workflow. (a) Original X-CT image; (b) Noise reduction
887 using an anisotropic diffusion 3D filter; (c) Conversion to an 8-bit binary image (Otsu
888 threshold); (d) Distance map computed from (c); (e) Inversion of (d); (f) Extended Minima 3d
889 operation from MorpholibJ library (Fiji) or Dilate Local Extrema 3d algorithm (Advanced
890 Morphology library in IPSDK) on the distance map image (d) to identify all the local minima
891 (seeds); (g) Conversion of local minima image (f) into a label image (seeds are assigned a
892 specific label); (h) Seeded-based watershed segmentation from (e) and (g); (i) Watershed
893 basins (h) multiplied or combined with a binary thresholded image (c) to get the final 32-bit
894 labeled connected component image.

895

896 Fig. 8 - Semi-automated segmentation workflow. (a) Original X-CT image; (b) Noise
897 reduction using an anisotropic diffusion 3D filter; (c) Conversion of (b) to 8-bit binary image
898 using manual thresholding; (d) Edge detection (morphological gradient); (e) Top hat
899 transform algorithm to extract small elements; (f) Inversion of (e); (g) Distance map
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901 adjusting, and erosion by one pixel to avoid overlaps), and (i) small seeds (Extended Minima
902 3d operation of Fiji, or Dilate Local Extrema 3d algorithm of IPSDK); (j) Combination of (h)
903 and (i) using OR logical operator; (k) Labelled seeds image; (l) Inversion of distance map (g);
904 (m) Seed-based watershed segmentation algorithm from (l) and (k); (n) Inversed watershed
905 lines; (o) Combination of (m) with (c) using AND logical operator; (p) Despeckle filter (Fiji)
906 or Remove Small Shape 3D filter (IPSDK); (q) Final labeled connected component (i.e.
907 particle) image (p).

908

909 Fig. 9 - (a) Two-dimensional view of MA-01 core sample along with the volumetric percent
910 of the different phases identified (heavy minerals, carbonates, silicates, clayey matrix, and
911 pores). (b) Histograms of the grayscale values of tsunami deposit sample.

912

913 Fig. 10 - (a) Two-dimensional view of BR-01 core sample along with the volumetric percent
914 of the different phases identified (heavy minerals, carbonates, silicates, clayey matrix, and
915 pores). (b) Histograms of the grayscale values of tsunami deposit sample.

916

917 Fig. 11 – Vertical variations of particle size distribution along core MA-01, calculated using a
918 500 μm step interval and a semi-automated image segmentation method (IPSDK software).

919

920 Fig. 12 – Vertical variations of particle size distribution along core BR-01, calculated using a
921 500 μm step interval and a semi-automated image segmentation method (IPSDK software).

922

923 Fig. 13 - Examples of particles observed in the tsunami deposit in their respective X, Y, and
924 Z-axis, and respective sphericity number.

925

926 Fig. 14 - Mean sphericity values as a function of depth along core MA-01, obtained with the
927 two software (Fiji and IPSDK) and the two different segmentation methods (automated and
928 semi-automated) for the entire image stack. Vertical variations of the mean sphericity of the
929 particles are compared with the abundance of marine shells (estimated from a manual count
930 on the X-CT images).

931

932 Fig. 15 – Stereographic projections (equal angle projection, lower hemisphere) of the
933 sedimentary fabric in core MA-01. Data is presented both in a raw format on the left (i.e.,
934 stereograms are calculated at a vertical step of 2.5 mm for all size fractions), and classified
935 according to different particle size fractions at a vertical step of 8 mm on the right.

936

937 Fig. 16 – Stereographic projections (equal angle projection, lower hemisphere) of the
938 sedimentary fabric in core BR-01. Data is presented both in a raw format on the left (i.e.,
939 stereograms are calculated at a vertical step of 2.5 mm for all size fractions), and classified
940 according to different particle size fractions at a vertical step of 4 mm on the right.

941

942 Fig. 17 – Comparison of four different particles (a-d) between the results of automated
943 segmentation (e-h), and semi-automated segmentation (i-l).

944

945

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947

948 Table 1: Computation time versus image processing steps with IPSDK and Fiji.

949

950

951 SUPPLEMENTARY MATERIAL

952

953 Suppl. 1 – Python code of the automated segmentation method for IPSDK.

954

955 Suppl. 2 – Python code of the semi-automated segmentation method for IPSDK.

956

957 Suppl. 3 - Python code of the semi-automated segmentation method for Fiji.

958

959 Suppl. 4 - Kernel density distribution (KDE) plots of equivalent particle diameter for core

960 MA-01. KDE represents the statistical data using a continuous probability density curve in

961 one or more dimensions. Numbers in subtitles refer to the X-CT image numbers from the base

962 (image n° 0) to the top of the tsunami deposit (image n° 8747).

963

964 Suppl. 5 – Vertical variations of the equivalent mean and maximum Diameters obtained with

965 the two software (Fiji and IPSDK) and the two different segmentation methods (automated

966 and semi-automated) for core MA-01.

967

968 Suppl. 6 - Mean and max particle size vs depth along core MA-01, at four different step sizes.

969

970 Suppl. 7 - Kernel density distribution plots of sphericity index for core MA-01. Numbers in

971 subtitles refer to the X-CT image numbers from the base (image n° 0) to the top of the

972 tsunami deposit (image n° 8747).

973