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1 **Short term displacements of marked pebbles in the swash zone: focus on particle shape and size.**

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7

8 **Abstract**

9 In this paper, two short term experiments with tracers on a mixed beach are presented. The aim was to
10 understand how the size and shape of pebbles can affect their transport under low energy conditions.
11 Sediment transport was studied by means of RFID technology to univocally monitor every single marked
12 pebble. A size subdivision of injected pebbles was conducted based on three classes ("Big" from -5.5 to -6.5
13 phi; "Medium", from -5 to -5.5 phi; and "Small", from -4.5 to -5 phi). Two recoveries were realised 6 and 24
14 hours after the injection. During a single day, the wave motion was very low in the first experiment and low
15 to moderate in the second (never exceeding 0.4 m). The results showed that discs are less dynamic than
16 spheres but can cover greater distances. Regarding the sediment size, "Big" pebbles are less dynamic if
17 compared to finer classes, and they move preferentially down the swash zone toward the step or do not move
18 up-slope if already at the step. Very low and steady energy conditions facilitate cross-shore and offshore
19 movement of pebbles, rather than a slight raise in wave height producing predominant longshore transport
20 even with non-marginal displacements. Low to moderate energy conditions can also produce some trend
21 displacement based on the pebble shape even though T-tests showed that shape was not statistically
22 significant for pebble displacement. The displacements of "Medium" and "Small" sized pebbles show a
23 statistical dissimilarity compared to the "Big" ones. To refine the velocity estimation necessary to initiate
24 pebble movement, the threshold velocity formulas known up to now should involve the shape parameter,
25 especially for the short term. Better knowledge of the relationship between the sediment's characteristics and
26 dynamics is critical to forecast the durability of replenishment material and to establish the suitability of fill

27 material relative to native beach material. Hence, a better understanding of the role of particle characteristics
28 is necessary.

29

30 **Keywords**

31 Tracer; sediment transport; particle shape ; mixed beach; swash; gravel nourishments.

32

33 **1. Introduction**

34 Several hydrodynamic factors exert significant control on sediment transport for gravel and mixed sand-
35 gravel beaches, and these factors are still poorly understood. A comprehensive review of these forces was
36 made in the recent past (Kirk, 1980; Mason and Coates, 2001; Buscombe and Masselink, 2006), but finding
37 clear correlations between sediment characteristics and hydrodynamic agents still represents a hard
38 challenge, especially in the swash zone. Gravel is not only larger, but usually varies over several orders of
39 magnitude greater than beach sands (Buscombe and Masselink, 2006) and this characteristic creates
40 extremely evident texture variations on coarse clastic beach surfaces, which cyclically raises the interest of
41 researchers. After the early papers written mainly around the 1970s and 1980s (Bluck, 1967; Carr, 1969;
42 McLean and Kirk, 1969; Carr et al., 1970; McLean, 1970; Carr, 1971; Gleason and Hardcastle, 1973;
43 Orford, 1975; Kirk, 1980; Caldwell, 1981; Williams and Caldwell, 1988; Isla, 1993; Isla and Bujalesky,
44 1993), a renewed interest in sediment transport based on different coarse particle characteristics formed
45 during the first decade of this millennium (Buscombe and Masselink, 2006; Ciavola and Castiglione, 2009;
46 Bluck, 2011; Bertoni et al., 2012a). Textural mosaics of different clast shapes and sizes are common and
47 different cross-shore size-shape zonation and modes of transport were demonstrated by many authors
48 (Bluck, 1967; Orford, 1975; Williams and Caldwell, 1988; Isla, 1993; Ciavola and Castiglione, 2009; Hayes
49 et al., 2010; Bluck, 2011), although the relative importance of size and shape in sorting sediment is yet to be
50 resolved (Buscombe and Masselink, 2006). According to Kirk (1980), the most complex aspect of mixed
51 beaches relates to sediment characteristics. Orford (1975) noted that the roles of size and shape cannot be
52 easily separated; using both factors is therefore well-advised to establish the degree of pebble zonation on a

53 beach before carrying out sedimentological characterization. Williams and Caldwell (1988) proposed a
54 model wherein the influence of particle size is more important on the sorting of sediments when energy
55 conditions are high, while particle shape predominates when energy conditions are low and cross-shore
56 sediment transport prevails. Because most of the cited papers relate to meso- or macro-tidal beaches, except
57 for Ciavola and Castiglione (2009), who provided insights on a micro-tidal beach, the aim of this work is to
58 develop further ideas on this type of beach attempting to discriminate whether shape and size affect
59 differentially pebble displacements in the swash zone under low-energy conditions . Furthermore, thanks to
60 the RFID technology that enables the unambiguous identification of pebbles (Allan et al., 2006; Bertoni et
61 al., 2010), it is possible to describe the movement of each individual particle according to its characteristics
62 such as shape and size. This tracing technique, according to Van Wellen et al. (2000), is currently best
63 suitable to obtain short-term transport rates on coarse-grained beaches.

64

65 **2. Regional setting**

66 The study area is a mixed sand-gravel beach located in Portonovo on the northern edge of the Conero
67 Headland in the central sector of the Adriatic Sea (Figure 1). The beach is located on the eastern side of the
68 village, it is approximately 500 m long and 20 to 60 m wide and is bounded by two boulder seawalls
69 protecting historical buildings. The southern portion of the beach is wider and slightly embayed, whereas the
70 northern part is narrower and straight. The beach was formed by a prehistoric landslide from the Conero
71 Headland (Coccioni et al., 1997). In this sector of the Adriatic Sea, the littoral drift is directed northwards
72 (Regione Marche, 2005), but this has no effect on Portonovo beach sediment transport because of its
73 longshore boundaries. Cliff erosion is the only sediment source as there is no river input; the natural
74 sediments consist of marls and limestones. The sediments vary from medium sand to cobble with a prevalent
75 gravel fraction mainly formed by pebbles. The beach face typically slopes 0.2, whereas the seabed seaward
76 of the step is approximately 0.01. The beach looks extremely heterogeneous regarding the surface sediment
77 grain size: sand and scattered gravel accumulations cover the backshore whereas the gravel fraction usually
78 occupies the swash zone, with granules and fine pebbles normally found on the berm and in the swash zone
79 while cobbles and boulders are usually found on the step. According to the Jennings and Shulmeister (2002)

80 classification of gravel beaches, Portonovo is a mixed sand and gravel beach (MSG), which is characterized
81 by a complete intermixing of sandy and gravelly sediments (Figure 2).

82 Figure 1 goes approximately here

83 Figure 2 goes approximately here

84 In 2010, a replenishment made of alluvial material compatible with the original sediment was carried out by
85 local authorities: pebbles and cobbles (4-100 mm in diameter) of limestone were used to contain beach
86 erosion. The total amount of fill material deployed on Portonovo beaches between 2006 and 2011 was
87 approximately 18500 m³: most of it was unloaded on the western side of the village (Figure 1, personal
88 communication by officers of the Regione Marche). The exact location and quantity of fill material released
89 in the eastern side of the town are unknown. The average tidal range at spring tide is 40 cm in the Ancona
90 area (Colantoni et al., 2003). The dominant winds come from the NE and SE, which correspond to the
91 directions of the main storms. The typical wave heights are between 0.25 and 2 m, with 20% of waves
92 coming from SE and 15% from NE (data recorded by the Ancona offshore wave buoy of ISPRA, Istituto
93 Superiore per la Protezione e la Ricerca Ambientale, in the period 1999-2006, Figure 3).

94 Figure 3 goes approximately here

95

96 **3. Materials and methods**

97 Two tracer experiments were set up at the Portonovo beach. The first one was carried out in March 2012, and
98 the second took place in April 2013. In both cases, the pebble displacement was investigated by means of
99 RFID technology, which was initially designed for subaerial pebble tracking (Allan et al. 2006) and recently
100 improved to work in the underwater environment (Bertoni et al. 2010). The technology is composed of two
101 devices: an RFID radio signal antenna (or RFID reader) and a transponder (or tag). Each tag has an
102 alphanumeric code that is required to unequivocally identify the pebble to which is coupled (Figure 4). The
103 antenna is connected to a laptop, where the tag code is shown once a tracer is detected; in addition, an
104 acoustic signal is emitted by the RFID reader as an additional warning sign of pebble detection. The electro-

105 magnetic field generated by the antenna is similar to a sphere with a 40 cm radius, which represents the
106 maximum detection range both underwater and in subaerial environments. According to Bertoni et al.
107 (2010), the detection range could be higher using high frequency radio signals, but this would have basically
108 impeded pebble detection underwater. The tracers were prepared by drilling a hole in each pebble to
109 accommodate the tag (Figure 4); the hole was sealed with a waterproof resin, reducing the original weight by
110 no more than 3 g. The tagged pebbles were randomly collected from the beach surface (backshore and beach
111 face), the only limitation being the size, which needed to be coarse enough to be drilled (Figure 4).

112 Figure 4 goes approximately here

113

114 *3.1 Experiment setup*

115 The two tracer experiments involved the same beach sector (Figure 1) and were carried out according to the
116 same scheme. Marked pebbles were deployed in the swash zone along 29 cross-shore transects spaced 10 m
117 (Figure 5A). Tracers were injected at 10:00 am and recovered after 6 and 24 hours. During both experiments,
118 the wave characteristics were recorded by means of an InterOcean S4 directional wave gauge. The device
119 was deployed on the bed seaward of the beach face to keep it underwater for the entire acquisition time (the
120 instrument was deployed at -1.5 m below Mean Sea Level, Figure 2A). Two time series of 20 min per hour
121 were provided, measuring the water level and wave parameters at a frequency of 2 Hz. For a water depth of -
122 1.5 m the observational capability of the sensor is up to 0.004 m. The uncertainty of measurement for wave
123 direction is ± 2 degrees.

124

125 The first tracer experiment was carried out in the early spring of 2012. The pebble population was sampled
126 on March 17th, two weeks before the experiment: no significant topographic modifications occurred on the
127 beach (Figure 6). At 10:00 am on March 29th, 145 marked pebbles were injected in the swash zone according
128 to the following order for each transect: one tracer was deployed on the fair weather berm crest; two tracers
129 on the swash zone mid-point; and two tracers on the step crest. Five marked pebbles were injected along
130 each profile without taking into account their size or shape (Figure 5B).

131 The second tracer experiment was realised in mid-spring of 2013. Sampling took place on March 22nd, one
132 month before the experiment: no significant topographic modifications occurred on the beach in the time
133 span between the sampling and the injection (Figure 6). At 10:00 am on April 23rd, 116 tagged pebbles were
134 deployed on every profile following the scheme: one pebble on the fair weather berm crest; two tracers at the
135 swash zone mid-point; and one pebble on the step crest. No tracer subdivision in terms of shape was
136 conducted at the injection; they were only sorted by the grain size. The mean diameter considered for tracer
137 size subdivision was the b-axis, obtained from sieving at 0.5 phi. Three classes were considered: the "Small"
138 class, characterised by a mean diameter with values between -4.5 and -5 phi (coarse pebbles according to the
139 Udden-Wentworth grain size scale, 24 to 32 mm); the "Medium" class, characterised by a mean diameter
140 with values between -5 and -5.5 phi (very coarse pebble according to the Udden-Wentworth grain size scale,
141 32 to 48 mm); and the "Big" size, characterised by a mean diameter with values between -5.5 and -6.5 phi
142 (very coarse pebble and small cobbles according to the Udden-Wentworth grain size scale, 48 to 96 mm).
143 One "Small" pebble was injected on the fair weather berm crest, one "Small" tracer and one "Medium" tracer
144 were released on the swash zone mid-point, and one "Big" marked pebble was placed on the step crest. Four
145 marked pebbles were deployed on each profile (Figure 5C). This type of injection scheme was conceived to
146 understand whether a selective transport based on the different size of the tracers operates under low energy
147 conditions. Due to the frequent variation of the sediment grain size in the swash zone, two different pebble
148 sizes were released at its mid-point ("Small" and "Medium" classes) to better represent the most typical
149 grain sizes. The tracers deployed on the step were compatible with the sediment naturally present on that
150 portion of the beach; pebbles slightly coarser than those characterising the natural sediment berm were
151 injected on the fair-weather berm. Because of the logistic limitations of the drilling operation, a mean
152 diameter between -4.5 and -5 phi was the smallest size that could be drilled. A tracer distribution based on
153 shape and size is shown in Figure 7 for both experiments.

154 Figure 5 goes approximately here

155 Figure 6 goes approximately here

156 Figure 7 goes approximately here

157 Although the swash zone is subjected to continuous surface sediment changes, a likely beach sediment
158 characterisation is shown in Table 1. Information on the beach sediments was obtained from surface
159 sampling conducted the day before the experiments. Grain size analysis was carried out by dry-sieving the
160 sediments at 1 phi mesh intervals for 15 min.

161 Table 1 goes approximately here

162 The tracer recovery campaigns were performed 6 and 24 hours after the injection for both experiments. The
163 pebble displacements were measured by means of an RTK-DGPS (Trimble R6, instrument accuracy
164 approximately 2 cm). The tracer displacements were considered significant if greater than 0.5 m in XY to
165 exclude shorter displacements wrongly caused by the antenna detection range (approximately 40 cm).

166

167 *3.2 Mixing depth evaluation*

168 During the second experiment an evaluation of the mixing depth was carried out. Three piles of 15 painted
169 pebbles were inserted at the back side of the fair-weather berm in order to appreciate the layer of sediments
170 interested by wave reworking after one day (Figure 8A). Piles were located at three different sites along the
171 beach: southern edge, mid sector and northern edge (Figure 8B). Disc shaped pebbles were chosen in order
172 to build a more stable pile; they were painted in blue and numbered from 1 to 15 for each pile (the 15th
173 pebble at the pile bottom, the 1st at the top, Figure 8C). The resulting height was reckoned adding the *c axis*
174 of each pebble which was previously measured with a caliper.

175 Figure 8 goes approximately here

176 *3.3 Statistical analysis*

177 Statistical analysis was performed by means of T-tests and box plots on both the pebble shape and size. Box
178 plots were used to describe the distributions of the pebble displacements according to shape and size
179 separately and also to their combined effect. The recovery distributions after 6 and 24 hours were compared
180 for each experiment. The size classes were divided according to the scheme used for the second experiment
181 injection. The shape categories were established according to the Zingg diagram (Zingg, 1935). Each shape

182 type was represented in the population used for the first experiment. Rods and blades were subordinate to
183 discs and spheres in terms of appearance. Due to their small quantity, the rods and blades were incorporated
184 with the discs to compare elongated shapes with spheres. In the second experiment, all the tracers belonged
185 to the sphere and disc shapes. Whether differential displacement was statistically significant between the
186 different shape and size classes of marked sediments (0.05 significance level) was tested. Because no size
187 discrimination was performed on the marked pebbles used in the first experiment (they all belong to the
188 "Big" class, which ranges from -5.5 phi to -6.5 phi), only the second experiment size data have been used for
189 the T-tests. T-tests were not used to analyse the combinational effect of shape and size given the scarce
190 quantity of data that would have resulted from an additional partition that takes into account both
191 characteristics.

192

193 *3.4 Threshold of tracer motion*

194 Estimations of the threshold wave orbital velocity for motion of pebble were computed and compared with
195 the tracer displacements that were actually measured during both experiments. S4 data have been used to
196 determine the threshold orbital velocity which was obtained using the graphical method of Soulsby (1997).

197

198 **4. Results**

199 *4.1 Wave climate and tracer recovery*

200 The wave motion during the first experiment was calm. Low energy was recorded throughout the entire
201 experiment with an average significant wave height of 0.09 m (max value 0.15 m) and a peak wave period of
202 4.3 s. The wave direction was strongly variable: no dominant direction was recognisable even though the
203 most frequent direction was NE (Figure 9). During the first experiment, tracer recovery after 6 hours was
204 99%, which slightly decreased to 93% after 24 hours. Only a few tracers moved more than 0.5 m (17% of the
205 whole) after the first recovery, with a maximum displacement of 2.6 m. Only 1% of the detected pebbles
206 shifted over a different morphological feature. After 24 hours, 42% of the recovered tracers moved more

207 than 0.5 m and the maximum measured displacement was 20 m. Considering the population shifting to a
208 different morphological feature, it increased at 17% after 24 hours. Cross-shore and offshore were the
209 prevalent displacement directions. Basically, most of the tracers were dragged down the beach face, moving
210 from the fair weather berm to the swash or the step zone (Figure 10B). Such a trend affected every shape
211 because no differences in the displacement direction related to pebble shape were noted. The tracer
212 displacements reached greater magnitudes on the northern sector of the beach with a stronger longshore
213 component compared to the southern sector (Figure 10B).

214 The energy conditions during the second experiment were higher compared to those of the first one. An
215 average wave height of 0.25 m (max value 0.38 m) with a peak wave period of 6 s was measured throughout
216 the experiment. The significant wave height hovered at approximately 0.3 and 0.4 m during the first ten
217 hours. The wave direction was basically stable within the ENE sector with a strong predominance from E,
218 which lasted 18 hours (Figure 9). Pebble recovery was 34% after 6 hours and increased to 47% after 24
219 hours. These lower percentages are connected to longer paths travelled by the tracers: the maximum
220 displacements measured after 6 and 24 hours were, respectively, 52 and 54 m. After the first recovery, 90%
221 of the detected pebbles exceeded the displacement threshold of 0.5 m; a similar value was reached after 24
222 hours (89%). The percentage of shifting to a different morphological feature was 38% after 6 hours and 49%
223 after 24 hours. The tracers did not show any peculiar trend in terms of direction after 6 hours. A prevalent
224 movement direction stands out after 24 hours: pebbles released at the swash zone's mid-point essentially
225 split towards the up-slope and down-slope locations. All the pebbles moved from south to north, with shorter
226 displacements in the southern part of the beach and greater displacements in the northern sector (Figure 10C,
227 10D). Disc-shaped pebbles travelled longer distances, and many of them ended up on the back of the berm.
228 Spheres covered shorter paths after 24 hours and did not move landward of the fair-weather berm (Figure
229 10C, 10D). Regarding the size of the marked pebbles, "Small" and "Medium" classes seemed to move
230 significantly even after 6 hours towards various directions (Figure 11A). All the sizes increased their
231 displacements after 24 hours, even though the "Big" class was the least mobile (Figure 11A). Many "Small"-
232 sized tracers, initially located at the swash zone mid-point or on the fair-weather berm crest, reached the back
233 of the fair-weather berm (Figure 11). "Medium"-sized pebbles essentially split from the swash zone mid-
234 point either up-slope towards the berm or down-slope to the step crest. "Big"-sized tracers basically moved

235 with short longshore paths in the southern part of the beach, never climbing up the swash zone slope. On the
236 contrary, the “Big”-sized tracers in the northern sector showed longer displacements and in a few cases
237 moved onshore, almost reaching the fair-weather berm (Figure 11).

238 Figure 9 goes approximately here

239 Figure 10 goes approximately here

240 Figure 11 goes approximately here

241 Regarding the second experiment it was also possible to analyse the combinational effect of shape and size.
242 “Big” class did not show any displacement difference between spheres and discs (Figure 12A, 12B).
243 “Medium”-sized tracers did not exhibit any peculiar movement during the 6 hour recovery (Figure 12C),
244 while during the 24 hour recovery (Figure 12D) spheres moved preferentially offshore. “Small” class of
245 tracers showed slight differences: especially 24 hours after the injection discs shaped pebbles moved behind
246 the berm crest, reaching higher positions if compared to the “Small” spheres (Figure 12E, 12F).

247 Figure 12 approximately goes here

248

249 *4.2 Statistical analysis*

250 After the 6 hour recoveries of both experiments, all the size box plots are skewed to the right except for
251 “Big”-sized pebbles (Figure 13A; 13B). The “Small” and “Medium” tracers moved significantly more
252 compared to the “Big” ones, having a larger distribution interval compared to the biggest size (Figure 13B).
253 Their median values are initially closer to the box bottom and then increase towards the end of the
254 experiment. This does not happen to the “Big” class, which seems to be quite stable at low displacement
255 values, especially for the median values. At the 6 hour recovery period, the “Medium” class has slightly
256 longer displacements compared to the “Small” one. After 24 hours, the “Small”-sized tracers have the largest
257 range, skewness and median values (without outliers) of any size class. The “Medium” class has the most
258 stable range throughout the 24 hours, although the median value increases in the second recovery; on the
259 other hand, the “Small” class has the largest stretch after one day, making it the most dynamic class (Figure

260 13B). The box plots of pebble displacement show that the "Big" class is less susceptible to large movements,
261 both 6 and 24 hours after tracer release. Although some "Big" pebbles moved up to 5 m from their initial
262 position 24 hours after the injection, their median values are quite low and gravitate towards the bottom of
263 the box (Figure 13A; 13B). "Big"-sized sediments seem to have a similar behaviour in both experiments.

264 Box plots of pebble shape are fairly different from one experiment to the other. In the first one, there is no
265 remarkable difference between elongated and spherical shapes. After 6 hours, the spheres reach larger
266 displacements compared to the elongated shapes, but they maintain roughly the same interval after 24 hours.
267 The elongated shapes look more static at first but then show a quite similar to slightly larger range compared
268 to the spheres after one day (Figure 14A). In each case, the median values are constantly close to the box
269 bottom (Figure 14A). The intervals of the box plots are much larger in the second experiment (Figure 14B).
270 Although the displacements are larger, the discs and spheres behave as they did during the first experiment.
271 After 6 hours, the disc-shaped pebbles are less inclined to motion than the spheres. The spheres show slightly
272 greater median values and larger intervals. After 24 hours, both shapes record larger displacements because
273 of increased wave energy, but the discs have a wider range than the spheres. Furthermore, the disc box plot is
274 skewed far to the right with a median value strongly adherent to the bottom. The sphere box plot seems to be
275 more balanced with a more limited interval and a median value perfectly set in the middle of the interquartile
276 range (Figure 14B).

277 Taking into account the combinational effect of shape and size some other peculiar behaviours of pebbles
278 can be appreciated from box plots of the second experiment. "Big" spheres resulted more dynamic than discs
279 since the first recovery. The larger displacements of "Big" spheres appeared fairly clear 24 hours after the
280 injection, when most of them moved from the injection position of approximately 10 m (median value) and
281 some of them up to 20 m (Figure 15A). The displacement interval of "Big" discs remained basically the
282 same even after 24 hours, with the box steadily stuck at the bottom and maximum displacements of
283 approximately 5 m (Figure 15A). "Medium"-sized discs recorded lower displacements than "Medium"
284 spheres 6 hours after the injection. This situation was completely overturned after one day (Figure 15B). The
285 interquartile range of "Medium" discs after 24 hours was the same produced by spheres of the same size
286 already after 6 hours even though the median values differed consistently (Figure 15B). "Small"-sized

287 spheres confirmed larger displacements if compared to the discs 6 hours after the injection. After one day the
288 situation was overturned as already showed by the “Medium” class even though with larger displacements
289 (Figure 15C).

290 T-tests on the pebble size data (Table 2) reveal that the "Big" tracers have significantly different
291 displacements compared to the "Medium" and "Small" pebbles, except after 24 hours, where no substantial
292 difference is noted. On the other hand, the "Small" and "Medium" tracer displacements are not significantly
293 different either after the two recoveries. Accounting for the 6 hour recovery (Table 2), the "Big"-sized
294 sediments show a significant dissimilarity compared to the other sizes. Statistically significant differences
295 are not present in Table 3 according to the shape of the marked pebbles. There is no movement
296 discrimination of the pebbles in terms of their shape for any recovery time, except for the first experiment
297 among the discs and spheres 6 hours after the injection.

298 Figure 13 goes approximately here

299 Figure 14 goes approximately here

300 Figure 15 goes approximately here

301 Table 2 goes approximately here

302 Table 3 goes approximately here

303

304 *4.3 Mixing depth evaluation*

305 After one day two of the three blue pebble piles were completely dismantled. As showed in Table 4, only the
306 “a” pile was not entirely wiped out because the 15th pebble, initially placed at the pile bottom, was recovered
307 in situ even after 24 hours. Therefore, a mixing depth of at least 30 cm was observed for the central and the
308 northern sectors of the beach, whereas a slightly lower layer of sediments was reworked at the southern edge
309 of the beach (about 25 cm, Table 4).

310 Table 4 goes approximately here

311

312 *4.4 Threshold of tracer motion*

313 The estimation of the thresholds of motion using the graphical method of Soulsby (1997) gave the following
314 results. Considering the first experiment, the graphical method gives a value of 1.1 ms^{-1} for the "Big" class,
315 which was the only size class used at that experiment. For the second experiment, the Soulsby's method
316 provides a value of 1.2 ms^{-1} for the "Big"-sized pebbles, 1 ms^{-1} for the "Medium" class and 0.9 ms^{-1} for the
317 "Small" class (Figure 16). The graphical method of Soulsby (1997) resulted fairly close to the actual wave
318 orbital velocities measured by the S4 wave gauge (Figure 16).

319

Figure 16 goes approximately here

320

321 **5. Discussion**

322 The tracer recovery percentages of the two experiments were quite different. This was determined by the
323 different wave energy conditions, which could be considered very low for the first experiment (average
324 significant wave height of 0.09 m; max value 0.15 m) and low to moderate for the second (average wave
325 height of 0.25 m; max value 0.38 m). In the 2012 experiment, the recovery percentage was very high and the
326 relocation of tracers onto a different morphological feature was fairly low. The downslope movement of the
327 tracers from the berm crest was the most notable evidence of the first experiment. According to Bertoni et al.
328 (2013), the process that caused the down dragging of pebbles is ascribed to the joint action of water level and
329 swash fluxes. This tendency was not caused by higher wave energy, but by incessant swash action reworking
330 the foreshore combined with the rise in the water level recorded during the night (Figure 9). The higher wave
331 energy in the second experiment generated a quite different trend in the pebble displacements. Two pebbles
332 with different sizes (one "Medium" and one "Small") were released at the swash zone mid-point.
333 Diversification in the displacement between those two sizes was not recorded, but a pronounced splitting of
334 the tracers injected into the swash zone was found. This could be easily imputed to the slope and gravity
335 actions, but it is not clear how some tracers went up to and over the berm while some others reached the step
336 down slope. It is probable that a sufficiently energetic uprush moved the sediments up onto the berm, while

337 an adequately energetic backwash dragged pebbles down towards the step. In both experiments, even though
338 a main trend was recognisable after one day, not every part of the beach showed the same displacement
339 patterns among the pebbles. The southern part of the beach, where the swash zone is steep and narrow, seems
340 to be distinguished by shorter pebble displacements compared to the northern section. The latter is more
341 exposed to wave action and looks like a "transfer zone", where a wider and milder sloping swash zone
342 creates a more comfortable space for pebble transportation. A different level of beach exposure to wave
343 motion emerged from the mixing depth evaluation: only the pebble pile inserted at the southern edge of the
344 beach was not completely dismantled after one day, while at least 30 cm of sediments were surely removed
345 by waves in the central and northern sectors. Similar values of mixing depth were measured on some steep
346 Portuguese beaches by Ciavola et al. (1997). The authors found that the sand-mixing depth is equal to 0.27
347 times the wave height at breaking. A value of mixing depth of 22 cm, comparable to ours results, was
348 observed on the beach of Faro associated to a wave height at breaking of 0.80 m and a wave period of 7.0 s.
349 During our second experiment in Portonovo (wave height of 0.25 m and wave period of 6 s) breakers were
350 plunging directly on beachface as also confirmed by a surfing scale parameter of 2.7. The beach face was
351 sloping at 0.14 as averaged value which allows to use the formula proposed by Ciavola et al. (1997). The
352 steepness and the high percentage of gravel which constitutes the beachface in Portonovo did not allow to
353 build a proper structure where to place a pressure transducer measuring the actual wave parameters at
354 breaking. Measurements provided by the S4 wave gauge are somehow related to wave conditions occurred
355 immediately offshore the wave breaking and visual observations suggest that wave height at breaking was
356 approximately 1 m which would correspond to a mixing depth value of 27 cm according to the relationship
357 established by Ciavola et al. (1997). Ciavola et al. (1997) noted an anomalous value of mixing depth in a
358 mixed sand and pebble beach in Hirono, Japan (Kraus et al., 1982). In the Japanese beach a small value of 3
359 cm was measured despite a wave height at breaking of almost 1 m. Although Portonovo is more similar to
360 Hirono from a sedimentological point of view, the mixing depth values estimated in our experiment are quite
361 similar to those observed in Faro by Ciavola et al. (1997). Further investigation are needed on the interaction
362 between sediment of different sizes (see sand versus pebbles or gravel) in order to evaluate more accurate
363 measurements of mixing depth.

364 In Portonovo the swash zone slope basically did not show any difference from south to north (0.22 - 0.23 in
365 the first experiment and 0.13 - 0.16 in the second one, Figure 6), but the higher exposure to wave action of
366 the central and northern beach portions likely allowed sediments to travel longer distances in those areas. As
367 confirmed by Bluck's works (Bluck 1967, 1999), if the beach system is in swash-alignment, the cross-shore
368 transport can dominate regardless of wave energy (see Nash Point facies type). Portonovo beach does not
369 show a perfect swash alignment and its slight embayment of the southern beach edge, which is also protected
370 by an alongshore seawall, creates inconsistency on pebble displacements from south to north. Hence,
371 longshore transport can easily occur in the more exposed areas of the beach (central and northern zone).

372 The results of the first experiment suggest that shape does not represent a discriminating factor for pebble
373 movement: very low energy conditions combined with "Big"-sized tracers created a premise for pebble down
374 dragging. Dissimilarities in the pebble displacements among different shapes of particles are more evident
375 when analysing the outcome of the second experiment, where smaller tracers were investigated and higher
376 wave energy occurred. This disparity seems to confirm what was already stated by McLean and Kirk (1969),
377 that is, size is the primary factor controlling the sorting trends of sediments and shape is a second order
378 factor. In the second experiment, many disc-shaped pebbles ended up on the back of the berm, while this did
379 not happen to the spheres. As stated by Ciavola and Castiglione (2009) during an experiment conducted in a
380 nearby sand-gravel mixed beach (Porto Recanati beach) under equivalent energy conditions, the uprush is
381 able to drag large, flat pebbles up onto the beach face. Once the pebble reaches the berm, the backwash
382 dissipates because of infiltration and the flattest pebbles are left there, while the more spherical ones roll
383 down the slope. This was also observed by Bluck (1967) and Isla (1993) based on surface sampling and
384 beach observations on macrotidal coarse-grained beaches; the same process was already described by
385 Dobkins and Folk (1970) on some mixed beaches under low and high energy conditions (Table 5). Spherical
386 and discoidal shapes behaved consistently during each experiment in terms of the displacement length. After
387 6 hours, the spheres moved further from the injection points than the discs, but after 24 hours the discs
388 covered longer paths than the spheres. This trend was confirmed by box plots focused on the combined effect
389 of shape and size except for the "Big"-sized pebbles. Wave motion recorded during the second experiment
390 was not strong enough to entrain discs of bigger size, rather it was able to move spheres of the same size
391 probably taking advantage of their capability to roll. Some authors found that discs have lower pivotability

392 than spheres (Shepard and Young, 1964; Bluck, 1967) and the latter move more easily in traction (Bluck,
393 1967) by taking advantage of their spherical shape. The longer distances covered by discs after 24 hours do
394 not mean that this shape is more dynamic compared to the spheres. As noted by Isla and Bujaleski (1993),
395 spheres are preferentially set into "saltation", although the bed is dominated by discs, blades and rods, which
396 means that spheres keep moving until they find a stable location to be incorporated into the sediments that
397 constitute the beach (Caldwell, 1981), moving more quickly through the pores of the beach surface than
398 other shapes (Bluck, 1967). The resulting difference in the behaviour of the two shapes at 6 and 24 hours
399 cannot be imputed to an increase in the wave energy because higher waves occurred within 10 hours of the
400 injection during the second experiment (the significant wave height remained between 0.3 and 0.4 m), while
401 the first experiment was characterised by quite low waves (average significant wave height of 0.09 m; max
402 value 0.15 m). According to Orford (1975), the influence of shape depends not only on the wave energy but
403 also on the wave phase and breaker type. The results from the shape displacements are not sufficient to say
404 that there is a correlation between the shape and distance travelled by pebbles, as Carr (1971) already noted.
405 Another aspect in need of in-depth investigation is the relationship between the shape of the pebbles and the
406 characteristics of the surface over which they move (Carr et al., 1970; Caldwell, 1981): an irregular coarse
407 bottom determines different types of pebble movements (Isla, 1993), and pebbles are preferentially entrained
408 over sandy surfaces (Nordstrom and Jackson, 1993). Sherman et al. (1993) found that the distribution of
409 shape and size facies is primarily controlled by location within the beach cusp systems. According to Bertoni
410 et al. (2012b), the primary factor controlling the pebble displacement is the modification of incident waves
411 induced by irregularities in the morphology of the sea bottom. A zonation of particle shape was not observed
412 on the Portonovo swash zone, but shape very likely exerts an influence on pebble transport at least under low
413 energy conditions and in the short term. As noted by Orford (1975), the roles of size and shape cannot be
414 easily separated, and it is easier to use both factors to discern possible pebble zonation on a beach. The
415 choice of focusing separately or combining the effect of size and shape on pebble movement should be done
416 considering the energy conditions when the displacement takes place. Williams and Caldwell (1988)
417 proposed a model wherein the influence of particle size is more important on sorting when energy conditions
418 are high and particle shape predominates when energy conditions are low (Table 5). At the Portonovo beach,
419 according to the size subdivision established only for the second experiment, only "Big" sized pebbles (-5.5 -

420 -6.5 phi class) showed a different behaviour relative to the two finer classes. Pebbles of "Small" and
421 "Medium" sizes (-4.5 - 5 phi and -5 - -5.5 phi classes, respectively) actually travelled greater distances than
422 those belonging to the "Big" class; in addition, this difference in displacement was statistically significant,
423 especially after 6 hours. The first 6 hours were characterised by moderate wave height (approximately 0.3 to
424 0.4 m up to 10 hours after the injection) that was not able to move "Big"-sized pebbles over the fair-weather
425 berm. According to the paths of the marked pebbles, no relationship between their size and the elevation
426 along the beach where they were detected was noted, which means that wave height is a subordinate factor
427 controlling pebble displacement under very low energy conditions (first experiment) and under low-to-
428 moderate energy conditions (second experiment). The swash zone slope, swash fluxes, run up levels and
429 gravity play a major role in dragging down or moving up the pebbles along the swash zone. Coarser pebbles
430 basically moved toward the step, not reaching the backshore under low-to-moderate energy conditions. As
431 stated by Carr (1969), coarser material on the backshore is presumably "stranded" during longshore transport
432 only under severe storm conditions. Later, Carr (1971) found a linear correlation between pebble size and the
433 longshore movement in the short term, which becomes exponential in the long term. A sort of longshore size
434 sorting caused by the vector imparted by the direction of the wave's approach can be recognised at the end of
435 the second experiment, given that "Small"- and "Medium"-sized tracers moved farther from their injection
436 positions compared to the "Big" pebbles (Figure 9; Figure 11). Because the conventional techniques (e.g.,
437 sediment samplings, beach observations) commonly provide an opportunity to recognise complex patterns on
438 beach surfaces related to the size and shape of pebbles (McLean, 1970; Kirk, 1980), coarse tracer research
439 needs to be supported by more sophisticated methods to improve the knowledge about the natural sieving of
440 pebbles. Cross-shore transport was prevalent in the first experiment, while longshore paths were more
441 evident in the second resulting from the higher energy conditions experienced. A short list of past studies
442 concerning the relationship between pebble transport and their characteristics is presented in Table 5.

443 Table 5 goes approximately here

444 Mixed beaches are dominated by swash action and the interaction between these flows and wave breakers
445 (Kirk, 1980). Uprush-backwash systems are responsible for most of the activity on these beaches (Kirk,
446 1980). Kirk (1975) measured swash velocities on some mixed sand and gravel beaches: the mean velocity at

447 the swash zone mid-point was 1.68 ms^{-1} ; the maximum swash velocity was 2.5 ms^{-1} . The backwash velocities
448 averaged 1.40 ms^{-1} . Other studies observed a higher uprush velocity of 3.5 ms^{-1} on sandy steep beaches
449 (Hughes et al., 1997; Masselink and Hughes, 1998). These velocities are comparable with the estimations
450 conducted by the graphical method of Soulsby (1997) used in this study. As already noted by Kirk (1975),
451 those velocity values are adequate to enable high transport rates for any sediment size on the foreshore.
452 Because the majority of the injected pebbles recorded larger displacements after 24 hours in both
453 experiments, the estimation of Soulsby (1997) seems to be plausible given that the threshold of motion for
454 each size is closer to the wave orbital velocities computed from the S4 data. Because nearshore wave heights
455 were used (the S4 was located very close to the shoreline, but not in the swash zone), the wave heights at the
456 breaker line would be preferred to improve the accuracy of wave orbital velocity estimation. Williams and
457 Caldwell (1988) provided insights on the relationship between pebble shape and swash flows. According to
458 the authors, when swash velocities (either uprush or backwash) approach the critical threshold for transport,
459 more easily suspended oblate sediments are thrown forward during the short-lived energy peak of the swash.
460 When non-marginal swash velocities occur, mass is more important than shape in determining sediment
461 transport (cross-shore or alongshore) (Williams and Caldwell, 1988). Regarding the interaction between
462 pebble size and swash fluxes, Isla (1993) supposed that an armoured deposit forms as flow decreases (during
463 the backwash), producing an inverse grading of the sediment (coarser sediments over the finer ones). As
464 expected and confirmed by many authors (Kirk, 1980; Van Wellen et al., 2000; Bertoni et al., 2013), the
465 swash zone was the most dynamic part of the beach even under low energy conditions.

466 Sediment characteristics and sources are the key components of nourishment projects for several reasons.
467 First of all, nourishment projects require a periodic maintenance that needs a planning of all the future
468 recharging and monitoring stages of feeding material (transport, abrasion rate, loss rate) and mostly find an
469 adequate sediment source. All beaches have specific sediment characteristics that fill material should meet,
470 such as size, colour, roundness, sorting and mineralogical composition, but this task makes the research of
471 fill material a hard challenge. At Portonovo beach, the ideal fill material for nourishment purposes should be
472 formed by sphere-shaped pebbles. It is fairly clear that spherical and well rounded material is not easy to
473 find, except for natural offshore deposits or after long laboratory treatment (Nunny and Chillingworth, 1986;
474 Smith and Collis, 1993). A bulk of spherical pebbles would start to move from the early stage of its

475 deposition and in a more consistent way compared to a similar amount of discoidal pebbles. Furthermore,
476 during storms, discs could be transported towards the beach edges and be unlikely reworked by normal wave
477 motion. An ideal beach constituted just by spherical pebbles would always keep moving with no
478 “permanent” erosive or accumulation areas, always responding in an active way to any energy condition.
479 Regarding the size to be adopted for a pebble replenishment, a dimension comprised between -5.5 and -6.5
480 phi (“Big” size, very coarse pebble and small cobbles according to the Udden-Wentworth grain size scale, 48
481 to 96 mm) is to avoid given its low mobility. “Big”-sized pebbles could be used to build step feature or
482 anything that should be more stable. “Medium” and “Small”-sized pebbles (coarse and very coarse pebbles, -
483 4.5 to -5.5 phi or 24 to 48 mm according to the Udden-Wentworth grain size scale) should be preferred for
484 feeding the beach in its swash and emerged areas in order to keep the system free to actively interact with
485 wave energy. Some authors remarked the loss of nourishment gravel after a certain time since the end of
486 replenishment (Takagi et al., 2000; Maddrell, 1996). Harley et al. (2014) analysed in a nearby beach (Sirolo, San
487 Michele - Sassi Neri) how a gravel nourishment responded to beach rotation processes which also affect Portonovo
488 beach: therefore, a better understanding of sediment characteristics is crucial for future nourishment purposes.
489 The use of natural sediment as fill material is always recommended, trying to meet as more as possible the
490 characteristics of native material.

491

492 **6. Conclusions**

493 The study presented here shows an original contribution to the understanding of the role of pebble
494 characteristics on controlling sediment transport. Discs can cover greater distances than spheres but are less
495 dynamic. Once lifted and shifted by swash flows, the discs can travel long paths, reaching a stable location
496 distinguished by feeble forces under low wave energy conditions (e.g., the rear of the fair-weather berm or
497 slope break between the swash zone and the beach step).

498 “Big”-sized pebbles (-5.5 to -6.5 phi) are less dynamic compared to the finer classes (“Medium”, -5 to -5.5
499 phi; “Small”, -4.5 to -5 phi). They are not able to reach the back of the fair-weather berm if initially deployed
500 at the step crest but can be easily dragged down to the swash or step zone if released on the berm crest, even

501 under very low energy conditions. Nevertheless the “Big”-sized spheres appear to be slightly more dynamic
502 than discs of the same size.

503 There is no statistical relationship between the shape of the pebbles and their displacements, although
504 different shapes respond to different forces. "Big"-sized sediments seem to have a similar behaviour in both
505 experiments, which is significantly different from that of the “Medium” and “Small” classes. Further
506 investigations focusing on particle shape are needed to identify the possible primary factors that control
507 pebble movement (e.g., divergences in beach slope, pebble size, beach exposure, and beach surface
508 sediment).

509 Very low energy conditions create a premise for the cross-shore and offshore movement of pebbles. In that
510 case, wave height has a marginal role on pebble movement, while beach orientation in relation to the
511 dominant wave direction seems to have a major role. A slight raise in wave height produces a predominant
512 longshore transport even with non-marginal displacements. Furthermore, low to moderate energy conditions
513 allow some trend displacement based on pebble shape.

514 Actual measurements of swash velocities, which are able to initiate pebble migration, should be obtained to
515 improve threshold velocity formulas, which currently do not include any shape parameter. It is believed that
516 shape can be a discriminant factor for the transportation of sediments having a mean size between the coarse
517 and very coarse pebble size classes (from 16 to 64 mm, respectively), at least under low energy conditions.

518 Because artificial replenishments made with coarse-clastic material have become more popular in recent
519 years, studies dealing in the shape, size and abrasion of pebbles have important implications. A good
520 knowledge of the relationship between the textural characteristics of sediments and their dynamics is crucial
521 to establish the suitability of fill material relative to native beach material. Rising costs are inevitable in the
522 case of replenishment with gravel or coarse-clastic material when not naturally present in huge quantities
523 (i.e., Adriatic Sea). Under these circumstances, the fill material is obtained from quarry processing. Quarry
524 waste needs artificial crushing to obtain the required sediment size, which should be as close as possible to
525 the native sediment. For nourishment purposes a spherical shape and a size comprised between -4.5 and -5.5
526 ϕ (24 to 48 mm) should be preferred since spheres of that size are more dynamic than discs and tend to

527 prevent the creation of permanent areas in erosion or in strong accumulation on the beach. Thus, a better
528 understanding of the role of particle characteristics is needed.

529

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535

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684 Table 5 - List of the most recent studies on the role of particle size and shape on coarse-clastic and mixed
685 beaches.

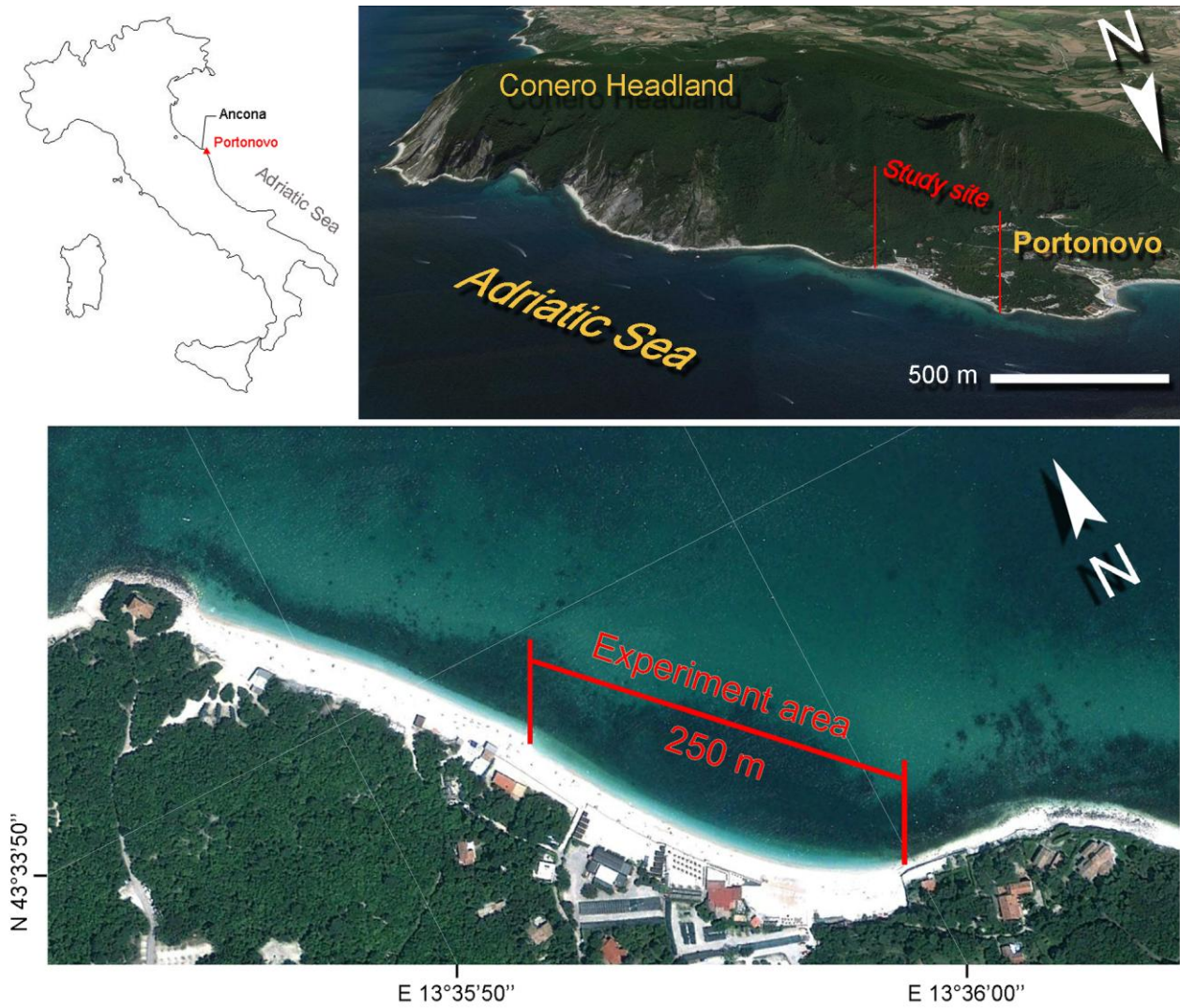
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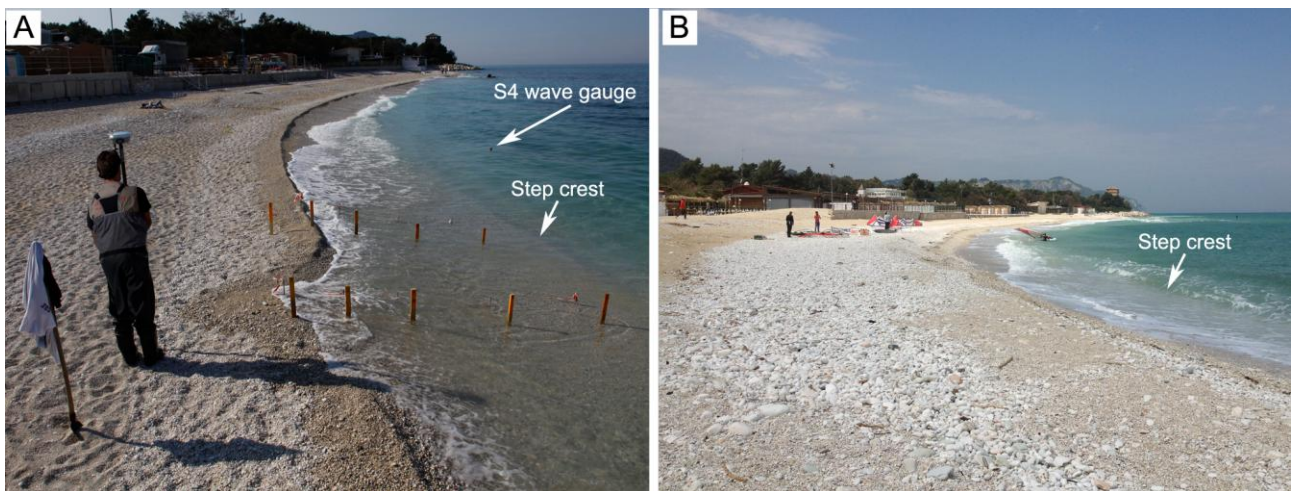


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Figure 1



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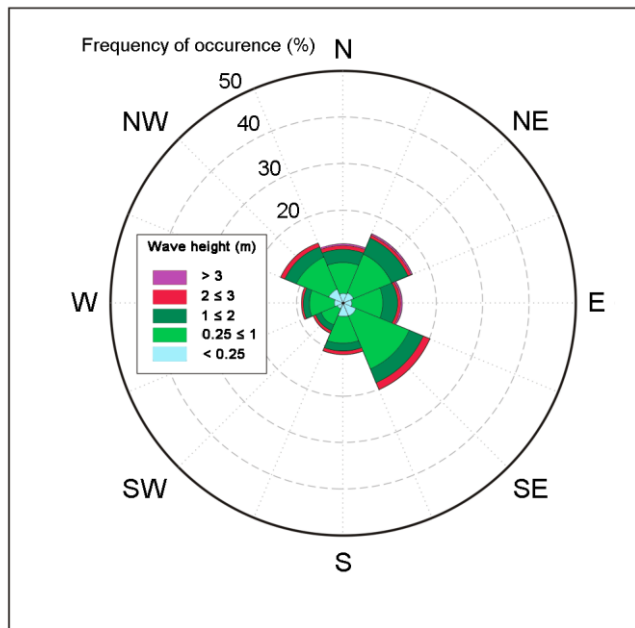
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Figure 2

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Ancona offshore buoy

1999 - 2006

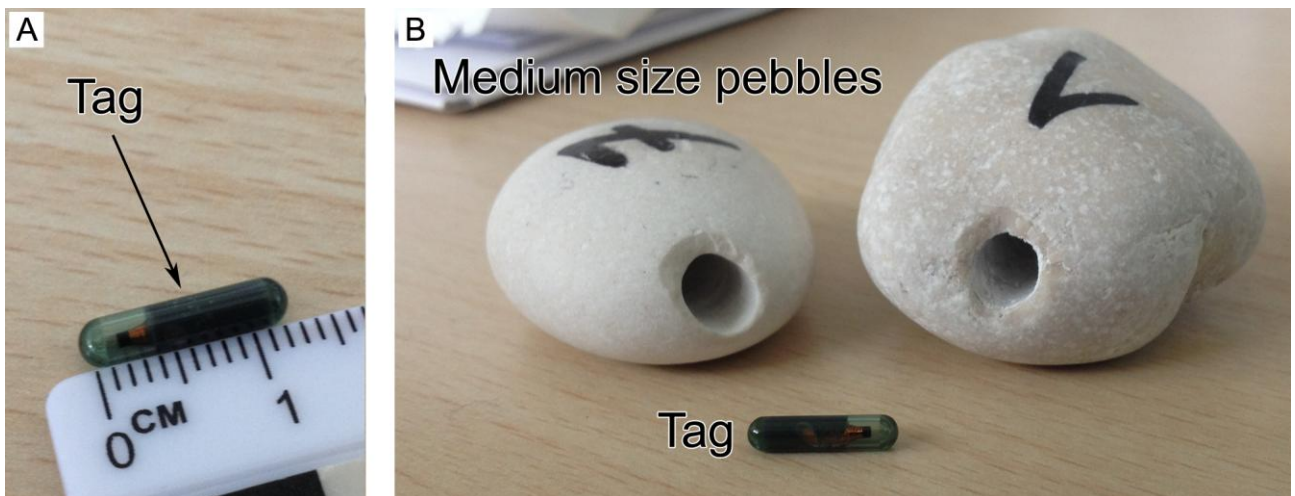


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Figure 3



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Figure 4

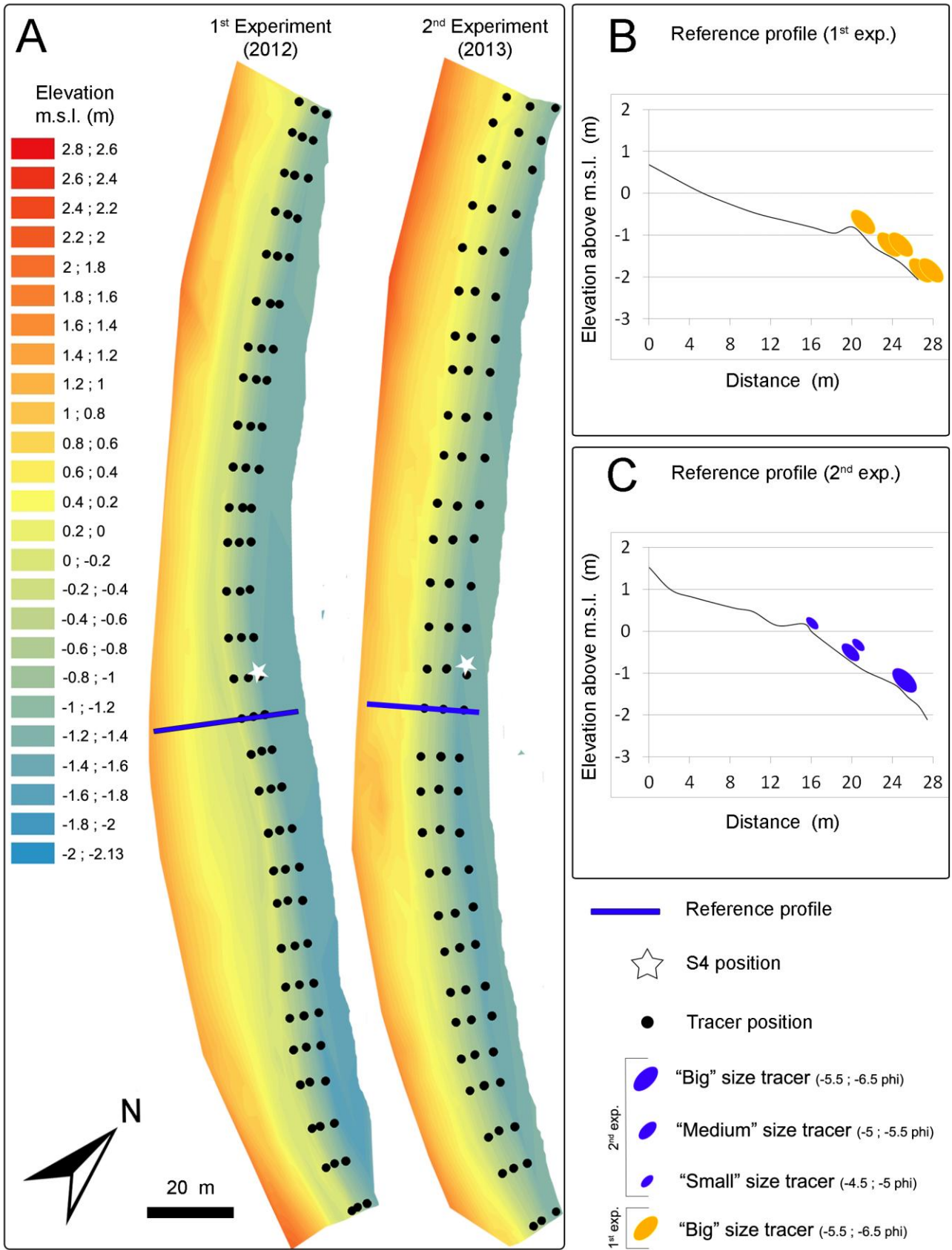
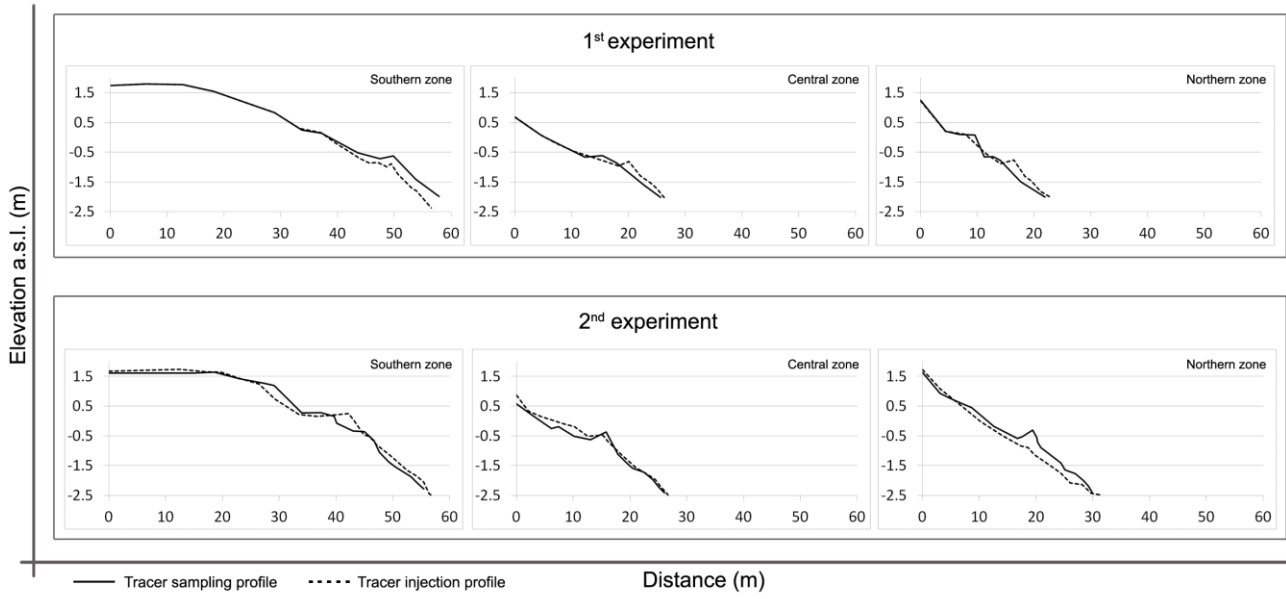


Figure 5

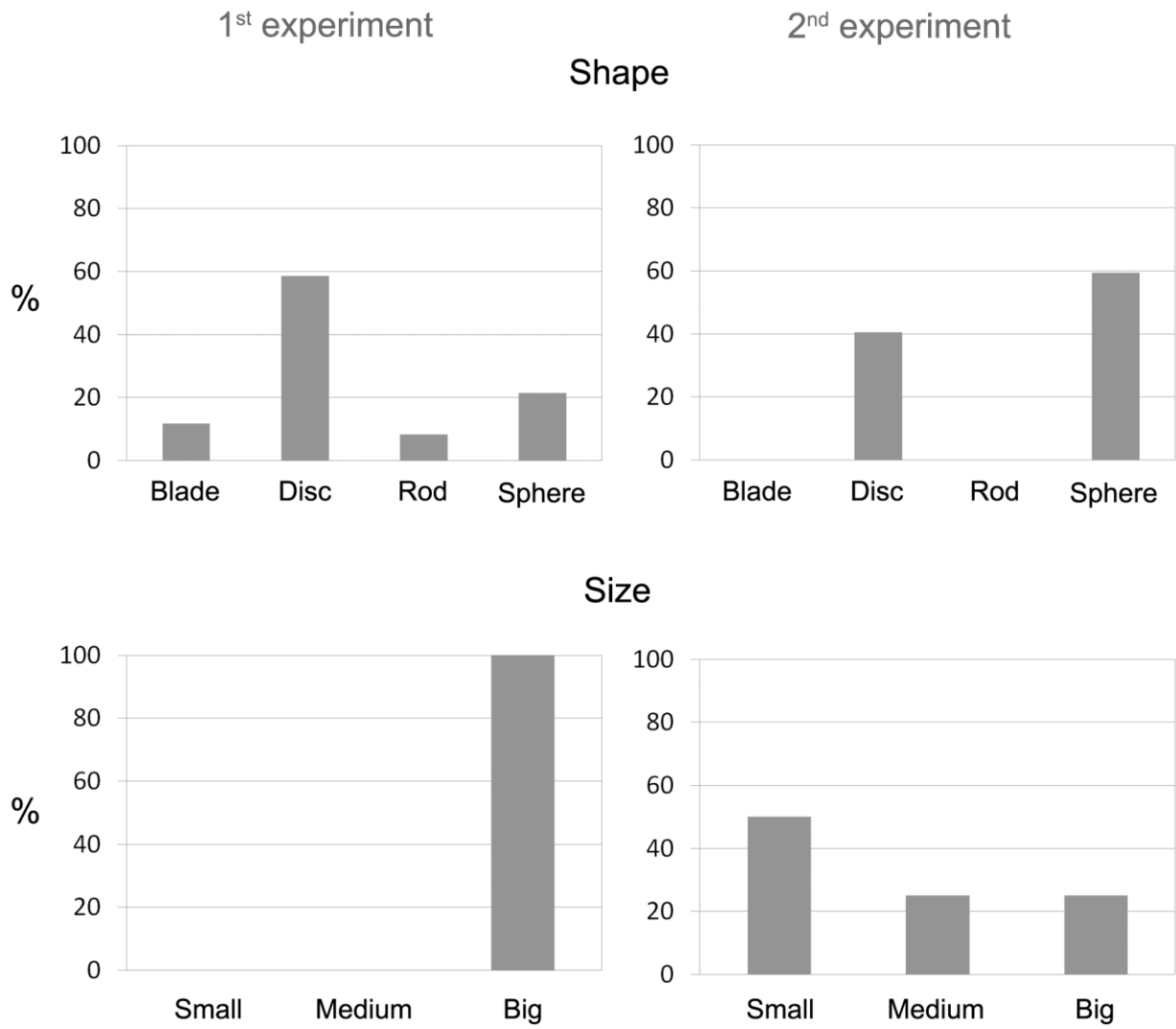


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Figure 6

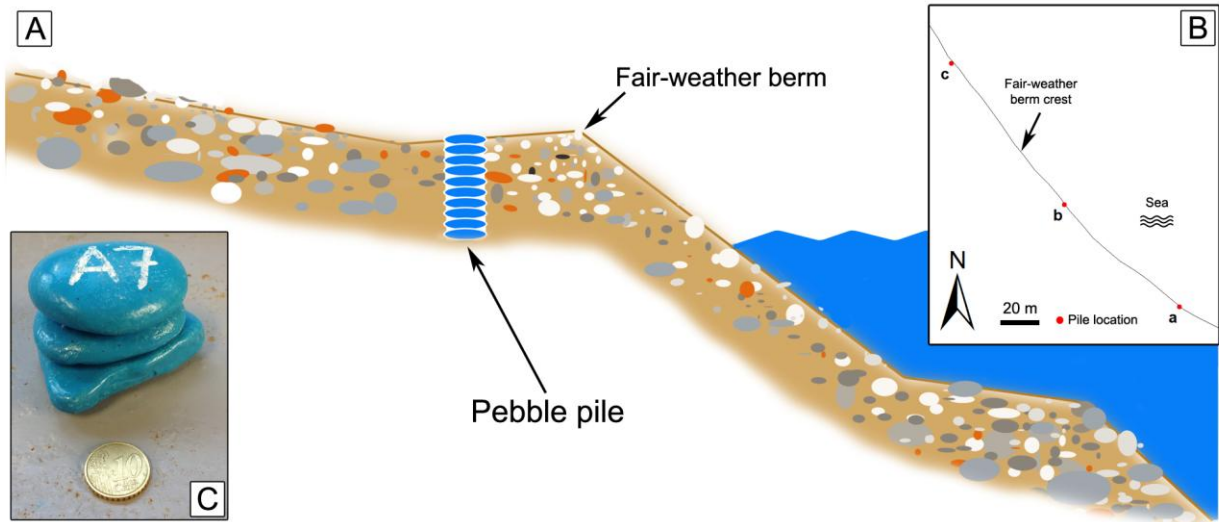


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Figure 7

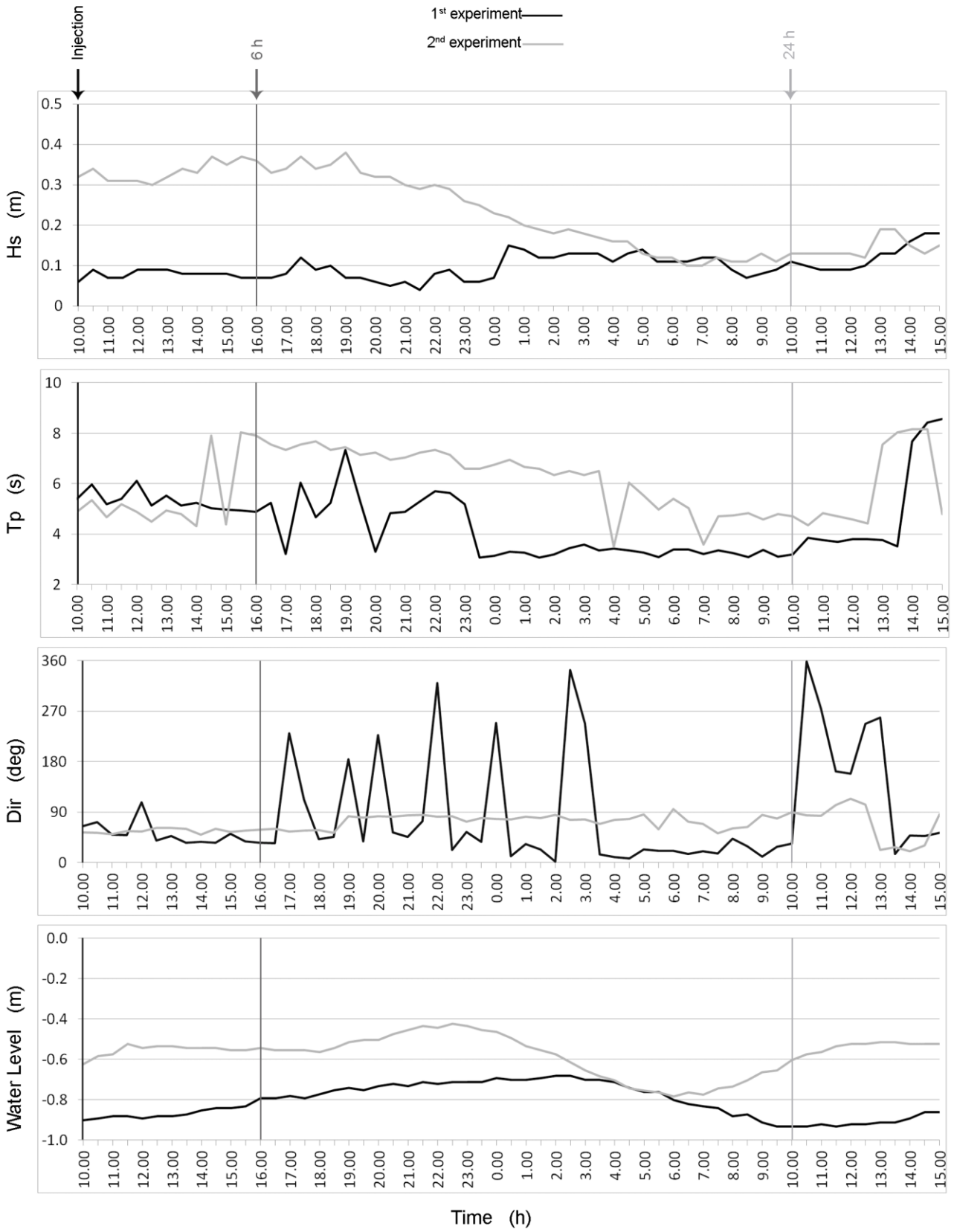


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Figure 8

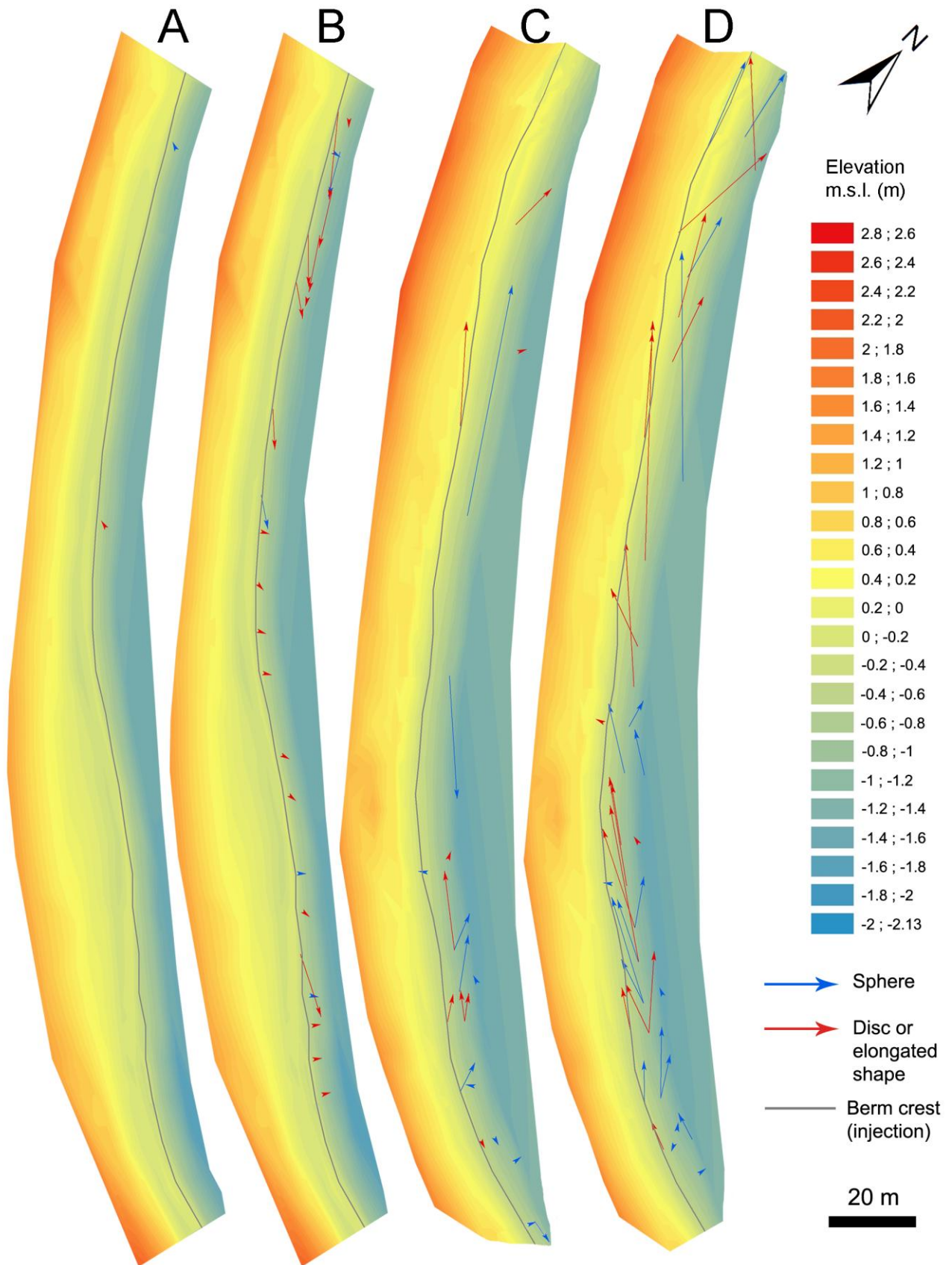


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Figure 9

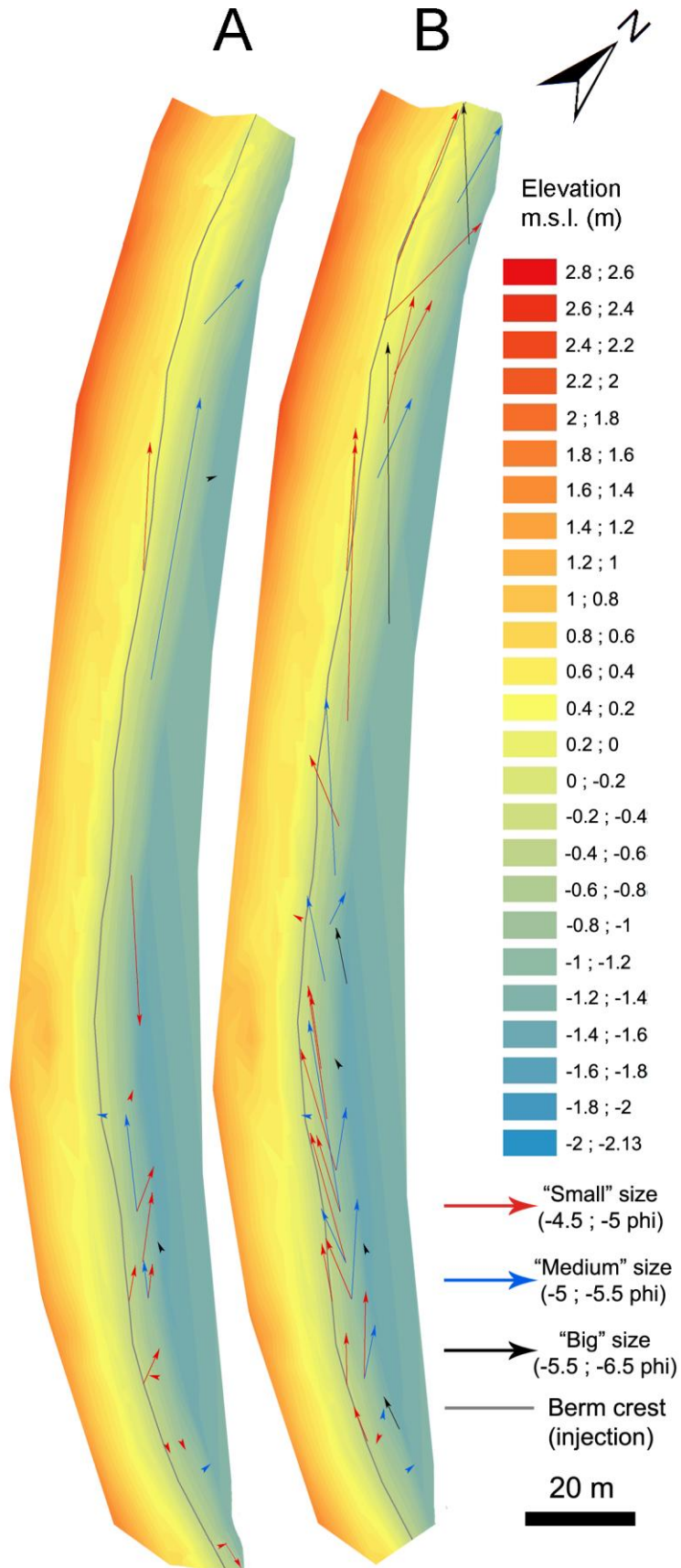


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Figure 10

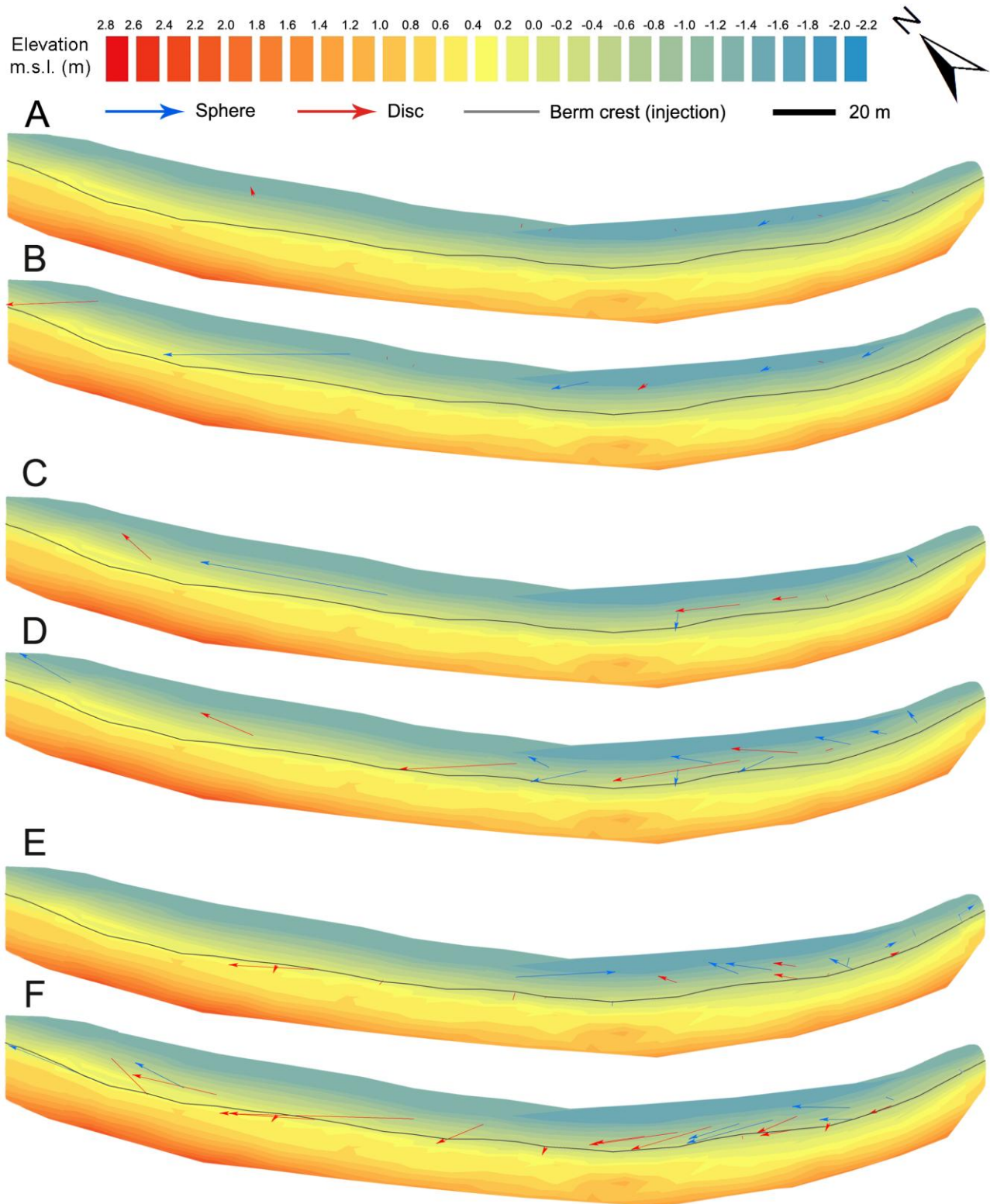


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Figure 11

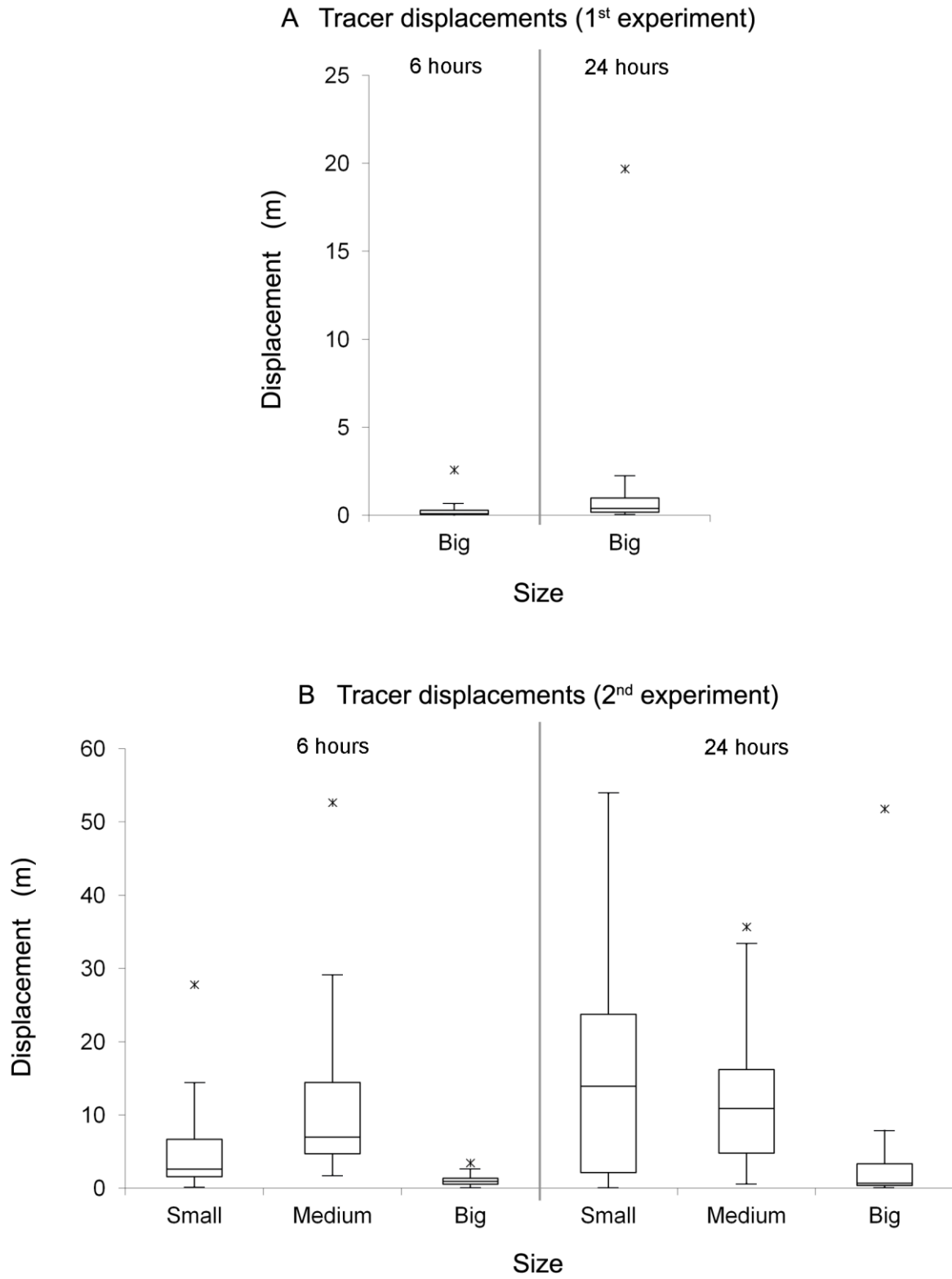


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Figure 12

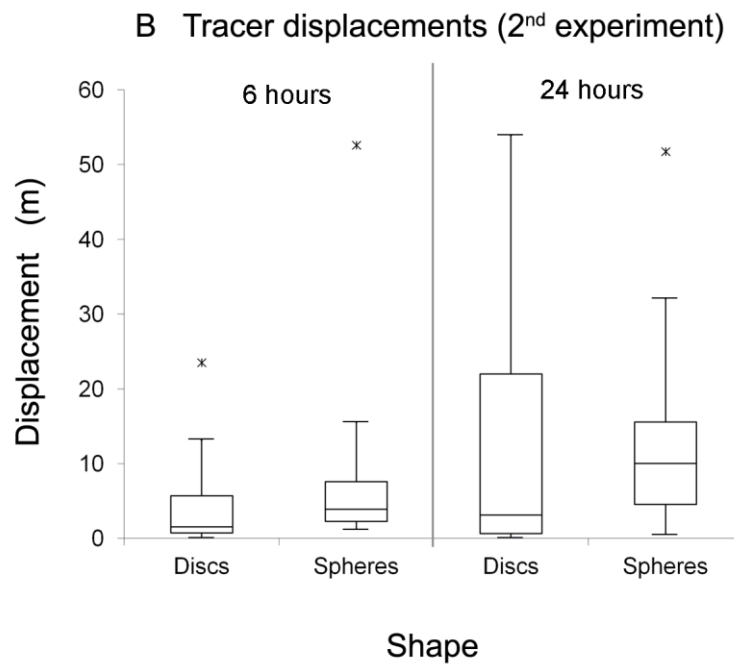
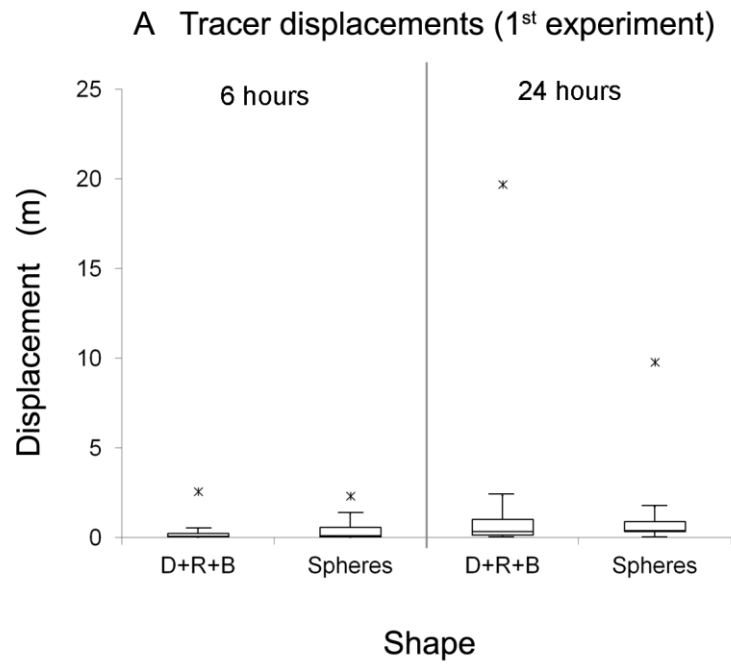


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Figure 13

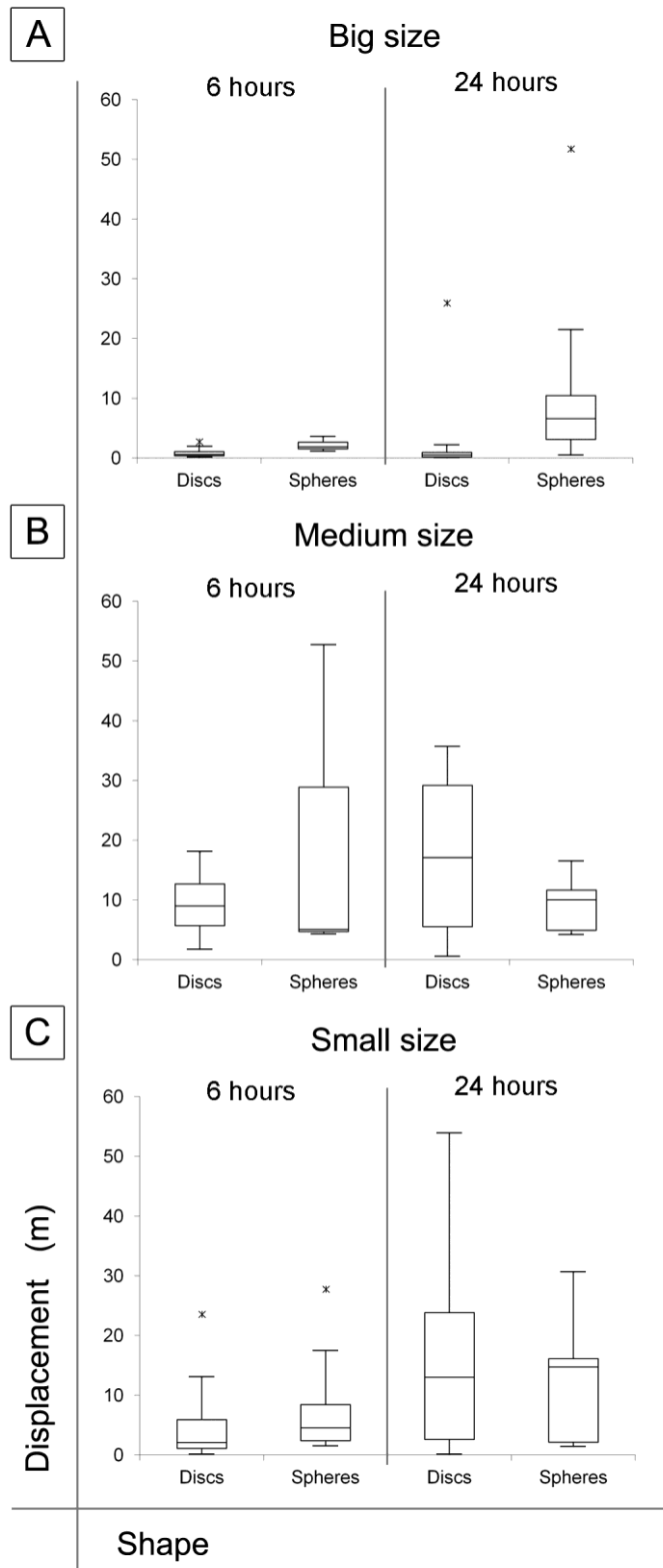


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Figure 14

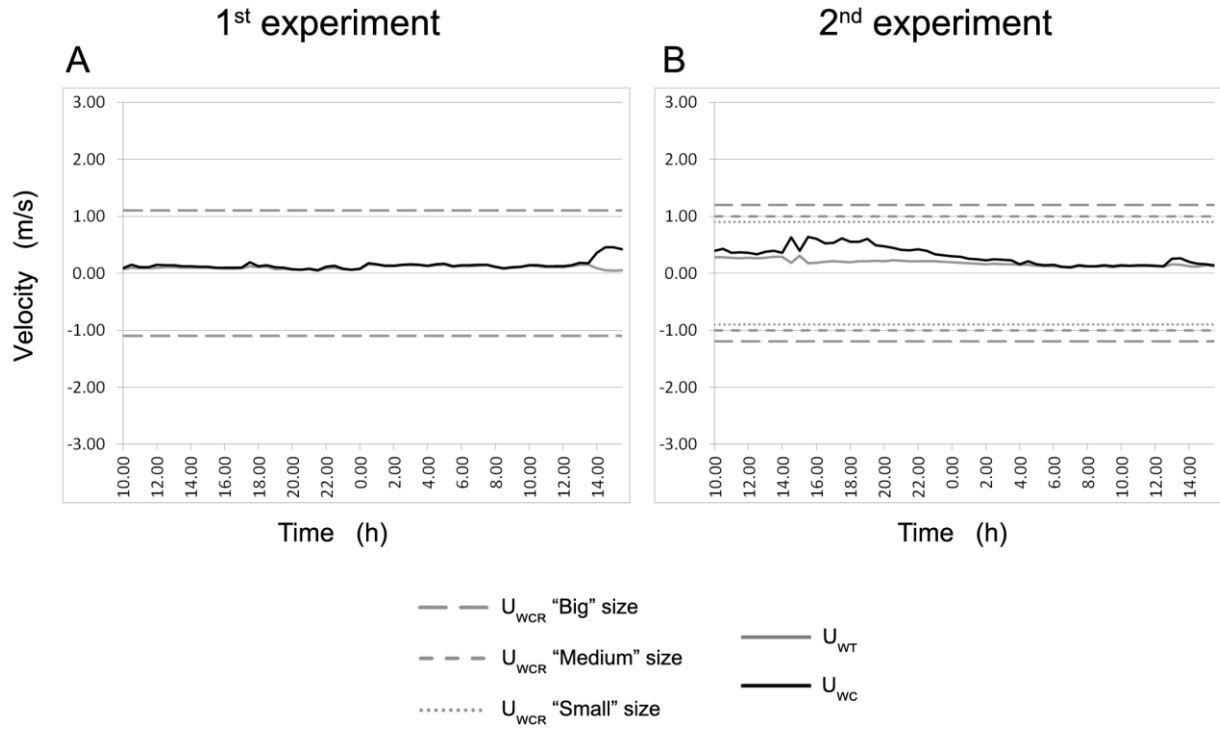


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Figure 15



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Figure 16

Morphological feature	Marked pebbles (size mm)		Beach sediments (size mm)	
	1 st experiment	2 nd experiment	1 st experiment	2 nd experiment
Berm	75	30	6	13
Swash	73	37	9	18
Step	79	71	65	-

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Table 1

SIZE (P < 0.05)	2 nd exp. - 6 h	2 nd exp. - 24 h
Small vs. Medium	0.088	0.704
Medium vs. Big	0.019	0.142
Small vs. Big	0.031	0.058

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Table 2

SHAPE ($P < 0.05$)	1 st exp. 6 h	1 st exp. 24 h	2 nd exp. 6 h	2 nd exp. 24 h
Disc vs. Sphere	0.028	0.889	0.121	0.821
Elongated (D+R+B) vs. Sphere	0.212	0.650	-	-

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Table 3

	Pile height (cm)		Mixing depth (cm)
	Injection	24 hours	
Pile a	26.15	1.5	24.65
Pile b	28.95	0	28.95 (at least)
Pile c	28.35	0	28.35 (at least)

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Table 4

Author	Focus on	Sediment size and type	Tidal regime	Wave energy	Beach type	Study method
Bluck (1967)	Pebble shapes and their sorting on the beach	Glacial pebbles (Subgreywacke, quartzite, limestone Macro or meso (not specified)		High	Mixed wide and flat beaches	Long term study Long term samplings
Carr (1969)	Pebble characteristics and their sorting under different wave	Quartzite and flint/chert pebbles	Meso	High	Limited by two cliffs 26 km long and 150- 200 m wide	1 year of surface and borehole samplings

Orford (1975)	Carr (1971)	McLean (1970)	Dobkins and Folk (1970)	Carr et al. (1970)	McLean and Kirk (1969)
<p>Role of shape and size of particles related to sediment zonation and From gravel to boulders in a sandy-silt matrix. Mudstone Meso or macro (not specified)</p> <p>Not described</p> <p>Embayed mixed beach</p> <p>1 year of repeated samplings</p>	<p>Relationships between distance travelled by pebbles and their size</p> <p>Quartzite and flint/chert pebbles</p> <p>Meso</p> <p>Medium/high (Hs max 1.2 m and mean Hs 0.5 m during the tracer</p> <p>Limited by two cliffs</p> <p>26 km long and 150-200 m wide</p> <p>Tracer experiments with non-native material</p>	<p>Sediment transport trends according to the size and sorting</p> <p>From medium sand to medium pebble</p> <p>derived from Meso</p> <p>High</p> <p>Mixed beaches, Rivers supply material</p> <p>Surface sampling and topographic profiles</p>	<p>Different pebble displacements relative to their shapes</p> <p>From sand to cobble</p> <p>derived from basalt rocks</p> <p>Micro</p> <p>High and low</p> <p>Mixed beaches</p> <p>Samplings</p>	<p>Pebble characteristics and the importance of the type of sub-strata</p> <p>Quartzite and flint/chert pebbles</p> <p>Meso</p> <p>High</p> <p>Limited by two cliffs</p> <p>26 km long and 150-200 m wide</p> <p>1 year of repeated surface samplings</p>	<p>Importance of size and shape of sediments on controlling beach</p> <p>Gravel size between 0.25 and 16 mm, grevwaacke derived</p> <p>Meso</p> <p>High (mean Hs 1-2 m; storm Hs 5-6 m)</p> <p>Mixed sand-shingle beaches</p> <p>1 year of repeated samplings on a monthly basis</p>

Ciavola and Castiglione (2009)	Isla and Bujalesky (1993)	Isla (1993)	Williams and Caldwell (1988)
Displacement of different pebble shapes under low and medium From medium sand to cobbles	Transport processes affecting different pebble shapes Glacial pebbles and cobbles	Displacement and arrangement of different sized pebbles Glacial pebbles and cobbles	Beach model based on the influence of particle size and shape Limestone pebbles
Micro	Macro	Macro	Macro
Low to medium (Hs from 0.1 to 0.45 m during the experiment)	High	High (Hs normally greater than 1.2 m)	High and low
Mixed sand and gravel beach 1 km long	Gravel spit	Coarse-clastic beaches	Wide and gently sloping foreshore
Short term tracer experiment with fluorescent paint	Samples collected by traps after tidal cycles	Surface samplings	1 year of repeated samplings.

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Table 5