

Impressive abrasion rates of marked pebbles on a coarse-clastic beach within a 13-month timespan

This is the peer reviewed version of the following article:

Original:

Bertoni, D., Sarti, G., Grottoli, E., Ciavola, P., Pozzebon, A., Domokos, G., et al. (2016). Impressive abrasion rates of marked pebbles on a coarse-clastic beach within a 13-month timespan. MARINE GEOLOGY, 381, 175-180 [10.1016/j.margeo.2016.09.010].

Availability:

This version is available <http://hdl.handle.net/11365/1010488> since 2017-06-28T13:24:05Z

Published:

DOI: <http://doi.org/10.1016/j.margeo.2016.09.010>

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25

26 Impressive abrasion rates of marked pebbles on a coarse-clastic beach within a 13-month timespan
27
28 Abstract
29 In this paper the abrasion rate on a coarse-clastic beach was evaluated by calculating the volume loss
30 recorded on indigenous pebbles within a 13-month timespan. The experiment was carried out at
31 Marina di Pisa (Italy) on an artificial beach that was built to counteract the erosion processes affecting
32 this sector of the coast. A total of 240 marble pebbles (120 rounded and 120 angular) were marked
33 using the RFID technology and injected on the beach. The volume loss measured after consecutive
34 recovery campaigns was progressively increasing, reaching the maximum value after 13 months (61%
35 overall). The average volume loss is consistent between rounded and angular pebbles at any time
36 (59.3% and 64.2% after 13 months respectively), meaning that the roundness is not a primary control
37 factor on abrasion rate. The pebbles that did not reach such abrasion rates after 8 and 10 months
38 (volume loss less than 20%) were found at heights equal or greater than 2 meters above mean sea level,
39 on the crest of the storm berm that formed during the strongest storms. This implies that the highest
40 wearing is achieved in the lower portion of the backshore, which is also the area that underwent major
41 topographic modifications. Here, sea water action might also exert chemical influence on the pebbles,
42 adding to the mechanical abrasion. The main result of this research, indicating an impressive volume
43 loss on beach pebbles in a short timespan, could be of key importance for coastal managers. The
44 optimization of coarse sediment beach nourishments is also relevant, taking into right consideration
45 that the volume loss due to sediment abrasion might exceed 50% of the original fill volume just after 1
46 year in the most dynamic portion of the beach.

47

48 Keywords: abrasion rate; pebble; coarse-clastic beach; beach nourishment; coastal management; Marina
49 di Pisa

50

51 1. *Introduction*

52

53 Since the early stage of the last century, sediment abrasion has always been a subject that raised interest
54 from the scientific community. According to Marshall (1927), abrasion “is the mere effect of pebble
55 rubbing against pebble”; this process is responsible for size reduction of sedimentary particles and also
56 affects their shape and roundness (Russell, 1938). The loss of volume among beach pebbles was
57 investigated in many ways and different causes of this process have been identified. Initially, laboratory
58 studies were preferred: steel drums and tumbler barrels charged with heavy loads of sediments and
59 different kinds of water (sea water, distilled water, dioxane) were adopted in order to define the main
60 factors accounting for pebble abrasion (Marshall, 1927; Russell, 1938; Bigelow, 1988). Later, laboratory
61 tests and field experiments focused on the interaction between indigenous beach materials and tracer
62 pebbles (exotic pebbles with color and texture dissimilar to the native ones) were also used (Latham et
63 al., 1998, Dornbusch et al., 2002; Dornbusch et al., 2003). Lately, field tests with native or fill material
64 are preferred in order to have a real case scenario of volume loss of beach sediments and to estimate
65 the durability of gravel nourishments. Dickson et al. (2011) and Bertoni et al. (2012a) adopted the
66 RFID technology to mark native pebbles on coarse-clastic and mixed beaches, experiencing significant
67 recovery rates (about 50%) for the experiment periods. Higher recovery rates (over 70%) were recorded
68 by Chen and Stephenson (2015) using abrasion baskets made of steel mesh. Pebble abrasion was first
69 investigated along rivers (Lewin and Brewer, 2002): in this environment, abrasion is a result of the
70 combination of different physical processes (e.g. collisions, friction) and some authors have already
71 proposed a mathematical model to predict the evolution of shape and size of particles during the
72 abrasion process (Domokos and Gibbons, 2012; Szabó et al., 2013). A similar model is still missing for
73 beach environments, especially to predict the evolution of fill material during the planning stage of
74 gravel nourishment. According to Nordstrom et al. (2008), periodic nourishment is required in all
75 beach nourishment operations conducted on eroding shores, but it may be required more frequently on
76 some particular kinds of gravel beaches because of the high rates of loss through abrasion. Thus, the
77 precise estimation of loss rate of fill material is crucial. The aim of the paper is to evaluate the abrasion

78 rate (here defined as volume loss per unit time) of individual marked pebbles on a real setting, within
79 certain timespans, taking into consideration the possible differences between angular and rounded
80 pebbles. Since beach filling using coarse sediments is a practice frequently adopted to protect coastal
81 areas and restore eroded beaches, it is of paramount importance to understand the time required to
82 smooth the angular pebbles and bring the pebbles to a grain-size that is favorable for tourism purposes.
83 As a consequence, the by-product of this experiment might be of great impact for coastal managers
84 because a considerable abrasion rate would lead to a fast volume reduction of the beach fill and to a
85 short life of the intervention, which in turn would determine loss of public money and trouble to
86 stakeholders and the population.

87

88 *2. Regional setting*

89

90 Marina di Pisa (Italy) is a small coastal village 11 km west of the city of Pisa, located along the southern
91 sector of the Ligurian Sea (Fig. 1a). Lots of citizens from the nearby areas gather there during the
92 summer because it is easily accessible and full of facilities and summer resorts, even though the natural
93 sandy beaches that used to characterize the area had been almost completely wiped out by strong
94 erosion processes. During the last 80 years this sector of the Tuscany coast has been subjected to a
95 huge retreat, whose main reasons have to be ascribed to the harsh load decrease of the major sediment
96 source, the River Arno (Fig. 1a). At the beginning the right side of the River Arno's delta was not
97 protected, leading to a land loss of more than 1 km in less than 50 years (Aminti et al., 2000; Pranzini,
98 2001). The left side underwent almost immediate defense interventions (breakwaters, sea walls, and
99 later groynes) to protect the buildings of Marina di Pisa, because the erosion processes quickly eroded
100 the wide beaches (about 300 m) and began striking the littoral promenade. In an attempt to increase
101 tourism attraction and coast safety, during the last 15 years the local authorities created a series of
102 artificial pebble beaches using waste from marble quarries. Being confined by groynes at both edges,
103 these beaches represented the ideal setting for a sediment tracing experiment (Fig. 1b). The beach

104 where the marked pebbles were actually injected is named Barbarossa: it is 180 m long and about 10 to
105 25 m wide (Fig. 1c). It is composed of a body of marble pebbles of about 30-to-90 mm in mean
106 diameter, lying over the native sandy bed. Barbarossa beach is bounded by two groynes made of large
107 boulders, and by a seawall that separates the backshore from summer resort facilities. The steepness is
108 significant on the beachface (about 19%; Bertoni and Sarti, 2011); it gets gentler offshore, reaching the
109 typical value of this portion of the Ligurian Sea (1%; Cipriani et al., 2001). The most frequent incident
110 wave direction is from the southwest, as major storms are usually driven by southwesterly winds
111 (Cipriani et al., 2001). The maximum tidal range is very low, hardly over 30 cm (microtidal
112 environment). The littoral drift is directed southwards throughout this sector of the coast (Gandolfi
113 and Paganelli, 1975), however, the groynes prevent any influence on the beach (Bertoni et al., 2012b).

114

115 3. *Materials and Methods*

116

117 The pebbles were traced using the Radio Frequency Identification Technology (RFID), which is a
118 reliable method to mark and identify individual samples. This technique has already been successfully
119 employed on coastal settings either on the subaerial environment (Allan et al., 2006; Curtiss et al., 2009)
120 and underwater (Bertoni et al., 2010; Grottoli et al., 2015). The RFID technology consists of an antenna
121 (*reader*) transmitting a continuous low frequency radio signal (125 kHz) to detect a transponder (*tag*),
122 which has previously been inserted into a pebble and it is univocally identified by a code. The tracers
123 were prepared for injection according to the procedure described in Bertoni et al. (2010). The 240
124 samples used for the experiment were randomly collected on Barbarossa beach: the only control factors
125 were *i)* the size and *ii)* the roundness. *i)* Pebbles with the b-axis shorter than 50 mm were discarded
126 because they would have likely been broken during drilling operations to insert the transponder. *ii)* Two
127 populations of pebbles were collected sorted by the roundness: 120 samples were angular and
128 representative of the sediments that were originally used to fill the beach; 120 samples were rounded
129 and representative of the pebbles that already underwent abrasion processes on the beach. Each pebble

130 was weighed with a digital scale (0.1 g of instrument error); the three axes (a, b, c) were measured with a
131 caliper (sensu Zingg, 1935). Both populations maintained similar characteristics in terms of average b-
132 axis length (rounded: 88.4 mm; angular: 97.2 mm) and of average dry weight (rounded: 854.9 g; angular:
133 888.6 g). Since the density of the marble pebbles can be assumed as constant (about 2700 kg/m³),
134 hereafter we refer to volume loss (%) instead of weight loss (%).

135 The tracers were injected on the beach along 40 transects orthogonal to the coastline on November 14th,
136 2013. Pairs of rounded and angular pebbles were placed on three spots along each transect in
137 accordance with the scheme described in Bertoni et al. (2012b): specifically, the crest of the fair-weather
138 berm, the swash zone, and the crest of the step. Each pair of tracers was selected beforehand in order
139 to select rounded and angular pebbles of similar volume and shape. The marked pebbles were
140 accommodated among the surface sediments and not just laid on the beachface. The injection position
141 of each tracer was recorded by a DGPS-RTK instrument, as well as the recovery position. The recovery
142 campaigns were carried out after 3, 8, 10 and 13 months to cover a 1-year timespan. Dry weight and
143 axis length of the tracers that were detected and retrieved were measured with the same scale and
144 caliper to enable comparisons to the initial measurements. The pebbles that were recovered were not
145 injected back.

146 Topographic surveys of Barbarossa beach were also carried out during pebble injection and recovery
147 activities. The surveys, performed by means of a DGPS-RTK instrument, were crucial to monitor the
148 geomorphological evolution of the beach. The resulting data were matched with injection and recovery
149 positions of the tracers to build consecutive maps of marked pebbles displacement using ArcGIS
150 software applications.

151

152 4. *Results*

153

154 At the end of the time frame of the experiment (13 months) the recovery percentage was not
155 particularly high (14%), even though it slightly increased after each campaign (Tab. 1). As a whole, only

33 tracers were retrieved: 16 rounded pebbles and 17 angular pebbles. Two of the 16 rounded tracers were found clearly broken, therefore their data were discarded. Though the recovery percentage was below optimal, the volume loss measured on the pebbles that were collected was, on one hand, of remarkable magnitude (Tab. 2) and also showed small variation. The tracers underwent an impressive evolution in shape and roundness (Fig. 2): even though the angular pebbles showed major modifications, their volume loss is comparable to that of the rounded pebbles (Tab. 2). The bulk of the tracers (20 pieces) were detected on the backshore, between the beachface and the base of the large storm berm that formed toward the seawall at the back of the beach (Fig. 3a). Eight pebbles were found on the upper portion of the backshore, which is characterized by a large storm berm formed during the strongest storms. Very few (3) pebbles were recovered underwater. As the topographic surveys clearly indicate (Fig. 3b), Barbarossa beach underwent significant modifications: the width generally decreased by 3 meters on the average throughout the entire length and accordingly, the steepness increased by approximately 6%. The topographic variations were particularly evident on the lower backshore (Fig. 3a): each survey showed substantial adjustments due to the generation of new storm berms after subsequent high-energy events. The large storm berm towards the seawall widened between tracer injection and the second recovery campaign, but it did not experience any major modification during the summer; conversely, the storm berm got steeper in December 2014, reaching the highest height (3 m).

174

175 5. Discussion

176

The unexpectedly low recovery rate was probably determined by the strong, lengthy storms occurred during the time frame of the experiment, especially in the first months (Fig. 3c): in particular, the intense storm occurred after just 6 days (20 November 2013) caused a profound reworking of the area where the pebbles were injected (Fig. 3a). As experienced in other works (Allan et al., 2006; Dickson et al., 2011; Bertoni et al., 2012b), another reason accountable for the low recovery rate might be the

182 burial of marked pebbles under the 40 cm detection range of the RFID antenna, especially in the storm
183 berm or in the underwater portion of the beach. In a tracing experiment carried out on the same beach
184 in 2009 (Bertoni et al., 2012b), the recovery percentage exceeded 50% after 2 months, but the storms
185 occurred in that timespan were shorter in duration than that of November 2013. Based on the recovery
186 of two broken pebbles and of a marble cap used to plug the transponder, breakage was likely an
187 additional factor that led to such limited recovery rate: the series of high-energy events occurred in that
188 timespan likely increased the probability of violent collisions between the clasts. While powerful waves
189 determine an increase of broken pebbles, still it is not possible to evaluate whether they are responsible
190 of the utmost wearing of the sediments, considering that significant pebble displacement is expected
191 also during fair-weather periods (Bertoni et al., 2013).

192 The impressive abrasion rate (an average of more than 60% after 13 months) observed in this
193 experiment is the sum of pebble friction and collisions due to wave motion under high-energy and low-
194 energy conditions: just 4 tracers showed a volume loss less than 20% after 8 months. Those tracers
195 were recovered on the crest of the storm berm, about 2 m above mean sea level: they underwent little
196 wear because once they were transported to such level on the beach, they did not experience any
197 further transport process since waves with lower energy could not reach the highest storm berms.

198 The considerable modifications the backshore underwent during the time frame of the experiment are
199 an additional aspect that can possibly explain such a scant recovery rate. The storms occurred during
200 the first interval (November 2013 – February 2014) concurred to increase size and height of the highest
201 storm berm, which showed an evident accumulation towards the seawall especially in the central-
202 northern portion of the beach (Fig. 3b). Several tracers might have been pushed landward and buried
203 during the formation of the storm berms. During the second interval (February 2014 – July 2014) only
204 one strong storm occurred, followed by a series of mild high-energy events. As a result, the storm berm
205 was characterized by a different evolution: the crest height slightly decreased, while the base widened as
206 a terrace about 9 m wide formed in the central sector of the beach. Apparently, the scour at the base of
207 the storm berm might have determined the collapse of the high crest and a consequent accumulation in

208 the mid-section of the backshore. The absence of relevant high-energy events during the summer (third
209 interval: July 2014 – September 2014) did not prevent significant modifications of the middle and low
210 portions of the backshore (Fig. 3a), confirming that low-to-mild wave states do produce remarkable
211 adjustments (Bertoni et al., 2013; Grottoli et al., 2015): even though they involved mainly the surface
212 layers of pebbles (Dornbusch et al., 2003), these morphologic changes allowed to recover several
213 tracers. The role of low-energy states and fair-weather periods is not negligible for pebble abrasion: as
214 already stated by Chen and Stephenson (2015) there is an “*abrasion zone*” on coarse-clastic beaches
215 roughly corresponding to the swash zone, which is always active, and its landward extension depends
216 on wave energy.

217 The last interval (September 2014 – December 2014) was characterized by a succession of storms that
218 once again concurred to move the pebbles towards the seawall, resulting in the formation of a steep
219 storm berm. The mobilization of the entire backshore led to the extensive reworking of the sediments,
220 which helped unearthing several marked pebbles, whose abrasion rates were highest among all the
221 recovered tracers.

222

223 6. *Conclusions*

224

225 The tracing experiment carried out at Barbarossa beach (Marina di Pisa, Italy) within a 13-months
226 timespan showed that sediment roundness does not affect the abrasion rate of pebbles: angular and
227 rounded tracers recorded comparable volume losses within each time interval. This observation is in
228 accordance with theoretical predictions (Domokos and Gibbons, 2012). The most widely applied
229 empirical model for volume evolution during pebble abrasion is due to Sternberg stating that the
230 abrasion rate dV/dt is proportional to the volume V of the pebble itself (Sternberg, 1875). This model
231 also suggests that shape does not play a key role in abrasion rate, however, as the volume of the pebble
232 decreases, abrasion rate also decreases. Since recovered pebbles were not injected back, this model
233 cannot be verified with the current set of data.

234 The pebbles that did not display such high volume loss at any recovery campaign were found on the
235 higher level of the backshore, on the top of the storm berm crest, where mechanical and chemical
236 abrasions are negligible because wave action is active there only during major storms. Considering the
237 environmental implications, the chemical dissolution exerted by sea water on the pebbles needs to be
238 fully investigated: coarse-sediment beach nourishments are often realized where bathing is a key
239 resource for tourism activities and for the economy of the coastal areas, therefore sea water quality
240 requires to be adequately monitored immediately after the replenishment, when abrasion is supposed to
241 be highest. Arguably, abrasion shall slow down as rounding of the clasts has taken place. In this sense,
242 marble would not be the appropriate lithology, because is a soft rock and abrades quickly. It is still not
243 clear whether dissolved calcium carbonate affects negatively the water quality and/or accumulates
244 preferentially somewhere. A harder lithology may be an option: however, marble quarries are so close
245 to Marina di Pisa, whereas sources for harder rocks are more distant (if present). The costs of using a
246 different lithology may be so high that it could likely exceed the costs of projecting integrations to the
247 original nourishment. Furthermore, a change in lithology would change sand color as well as the beach
248 appearance overall. For users beach aesthetic is an important aspect which cannot be overlooked.

249 Barbarossa is a compartmentalized beach where the main morphological changes, in the absence of
250 large tidal excursions and longshore currents, are caused by storms. It is quite intuitive that the
251 continuous reworking of sediments due to tidal cycles on open beaches, as already found by
252 Dornbusch et al. (2003), can increase the abrasion rate. Nevertheless, in such small and confined
253 beaches as Barbarossa, the reworked bulk of sediments, which is prevented from leaving the system, is
254 always the same. Thus, the abrasion rate in this kind of beaches is clearly exacerbated and should be a
255 primary factor to be taken into account during the planning stages of a nourishment. Since abrasion
256 rate of angular and rounded pebbles was comparable and consistent after each survey, our results are
257 worth of consideration even though the number of recovered pebbles is scarce. We also remark that
258 our data has been recorded on individually identified pebbles and not by a statistical measurement or
259 laboratory test, so coastal managers should not neglect the volume loss recorded on the marked

260 pebbles used for this experiment. An aspect that still needs further investigation is the time
261 development of the abrasion process. There is currently no evidence if the process would slow down
262 with time, with the shape of the clasts reaching an equilibrium roundness level. In conclusion, the
263 abrasion rate needs to be considered as one of the most critical factor controlling volume loss of
264 coarse-sediment beach nourishments.

265

266 Acknowledgements

267

268 We are grateful to many friends and colleagues that helped us out at various stages of the experiment:
269 Dario Pacini and Giovanni Salcioli for laboratory activities; Fernanda Alquini, Alessandro Da Mommio,
270 Debora Guerzoni, Matteo Ruocco and Sarolta Bodor during the fieldwork. Wave measurements were
271 kindly provided by the Regional Hydrological Service (Tuscany). GD and TNSZ acknowledge the
272 support of Hungarian NKFIHgrant K 119245. Travel and accommodation expenses in Italy for TNSZ
273 were supported by Hungarian grant TAMOP-4.2.2.B-10/1-2010-0009.

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339 Figure 1. The study site: a) geographic localization of Marina di Pisa (Tuscany, Italy); b) aerial view of
340 the Barbarossa sector: the seawall at the back of the beach is evidenced with a red line (background
341 image from Google Earth); c) southern view of Barbarossa beach (picture shot on 25th February 2014).

343 Figure 2. Pairs of marked pebbles showing shape and roundness variations during each time interval
344 (left column: initial configuration; right column: post-recovery configuration). Pairs of rounded and
345 angular tracers are shown for each recovery campaign, except for the first campaign because the only
346 rounded pebble that was recovered was discarded as it was clearly broken.

348 Figure 3. The topographic maps show the geomorphologic evolution of the beach during the time
349 frame of the experiment (a); the black dots represent the injection position and the recovery position of
350 the tracers (the recovery position of the broken pebbles were not included in the maps). The evolution
351 over time is also showed by overlapping the traces of two reference profiles, RP1 and RP2 (b). Plot
352 showing wave height during the time frame of the experiment (c); wave data were provided by the
353 Regional Hydrological Service.

354

355

Figure 1

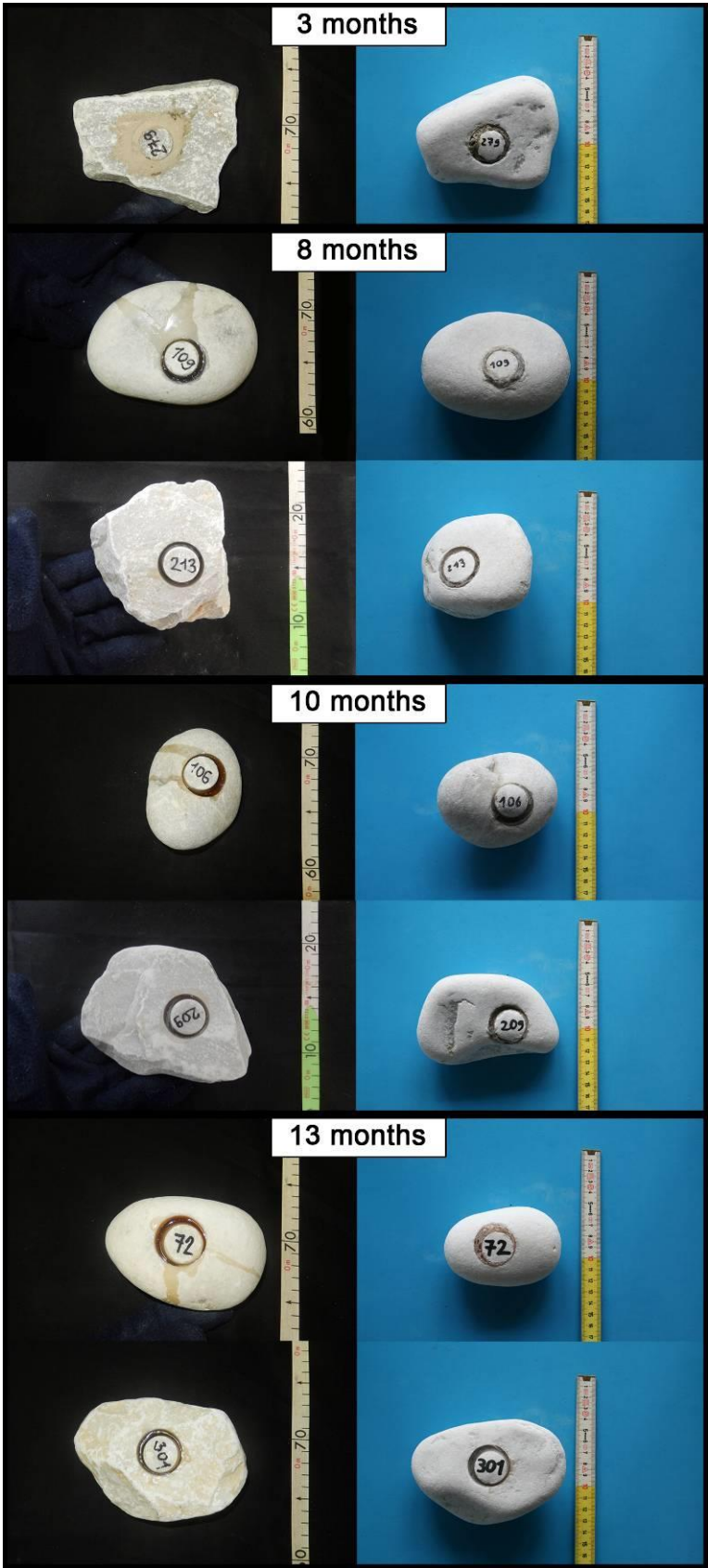


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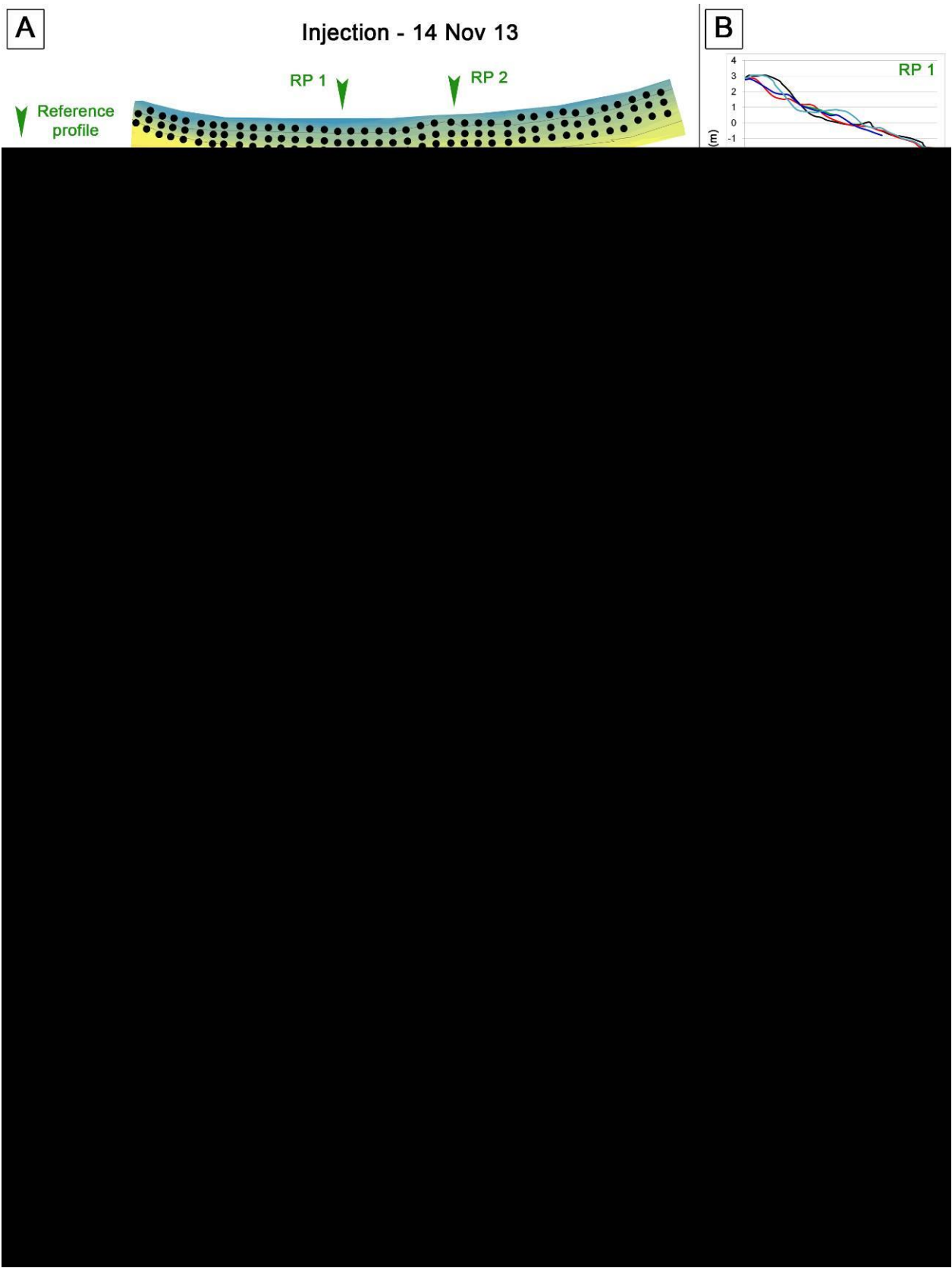
Figure 2



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Figure 3



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Table 1. Pebbles retrieved after each recovery campaign.

	3 months	8 months	10 months	13 months	TOTAL	RECOVERY (%)
RECOVERED	5	7	10	11	33	14%
ROUNDED	1	4	4	7	16	13%
ANGULAR	4	3	6	4	17	14%

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366 Table 2. Average volume loss measured on the pebbles that were recovered, sorted by rounded and
 367 angular. Broken pebbles were not considered.

VOLUME LOSS (%)	3 months	8 months	10 months	13 months
ROUNDED	-	17,8	25,6	56,1
	-	9,9	59,3	59,3
	-	28,5	5,8	64,1
	-	37,4	-	43,9
	-	-	-	65,6
	-	-	-	60,9
	-	-	-	64,9
<i>AVERAGE LOSS (%)</i>	-	23,4	30,2	59,3
ANGULAR	23,8	28,0	41,5	77,2
	15,5	32,3	66,4	71,6
	11,6	29,5	18,9	51,9
	28,4	-	48,4	56,0
	-	-	10,2	-
	-	-	23,8	-
<i>AVERAGE LOSS (%)</i>	19,8	29,9	34,9	64,2
TOTAL AVERAGE LOSS (%)	19,8	26,2	33,3	61,0

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