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1 **Liquefaction source layer for sand blows induced by the 2016 megathrust earthquake (Mw**  
2 **7.8) in Ecuador (Boca de Briceño)**

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14

15

16 **Abstract**

17 Numerous sand boils were generated in the alluvial plain at the mouth of the Rio Briceño valley  
18 (Ecuador) during the Mw 7.8 earthquake of April 2016. The area is characterized by a series of  
19 raised marine terraces formed as a consequence of the rapid tectonic coastal uplift during the  
20 Quaternary. On the basis of boreholes and geognostic investigations carried out within a mitigation  
21 project for liquefaction below a highway embankment and during post-earthquake surveys, we  
22 recognized 5 lithological units in the subsurface, reflecting the continental-marine and transitional  
23 sedimentation since the Last Glacial Maximum. We performed a comprehensive study of texture  
24 and petrographic composition of sand boils compared with sandy silts and silty sands of the buried  
25 sedimentary sequence in order to identify the source levels for liquefaction. The petrographic  
26 components, in particular the low content of bioclasts and carbonate fragments of the sand boils,  
27 allow to pinpoint a source layer made up of fine-grained silty sands located between 2 and 4.5 m  
28 depth (unit 2) whereas the deeper marine sands, richer in bioclasts, were not involved. The results  
29 support the idea that earthquake-induced liquefaction phenomena are not restricted to clean sands  
30 and well-sorted deposits, but may affect sand layers with significant amount of non-plastic silt.

31

32 **Keywords:** Earthquake-induced liquefaction, Sand blows, Ecuadorian coast, Sand composition,  
33 Holocene depositional sequences

34

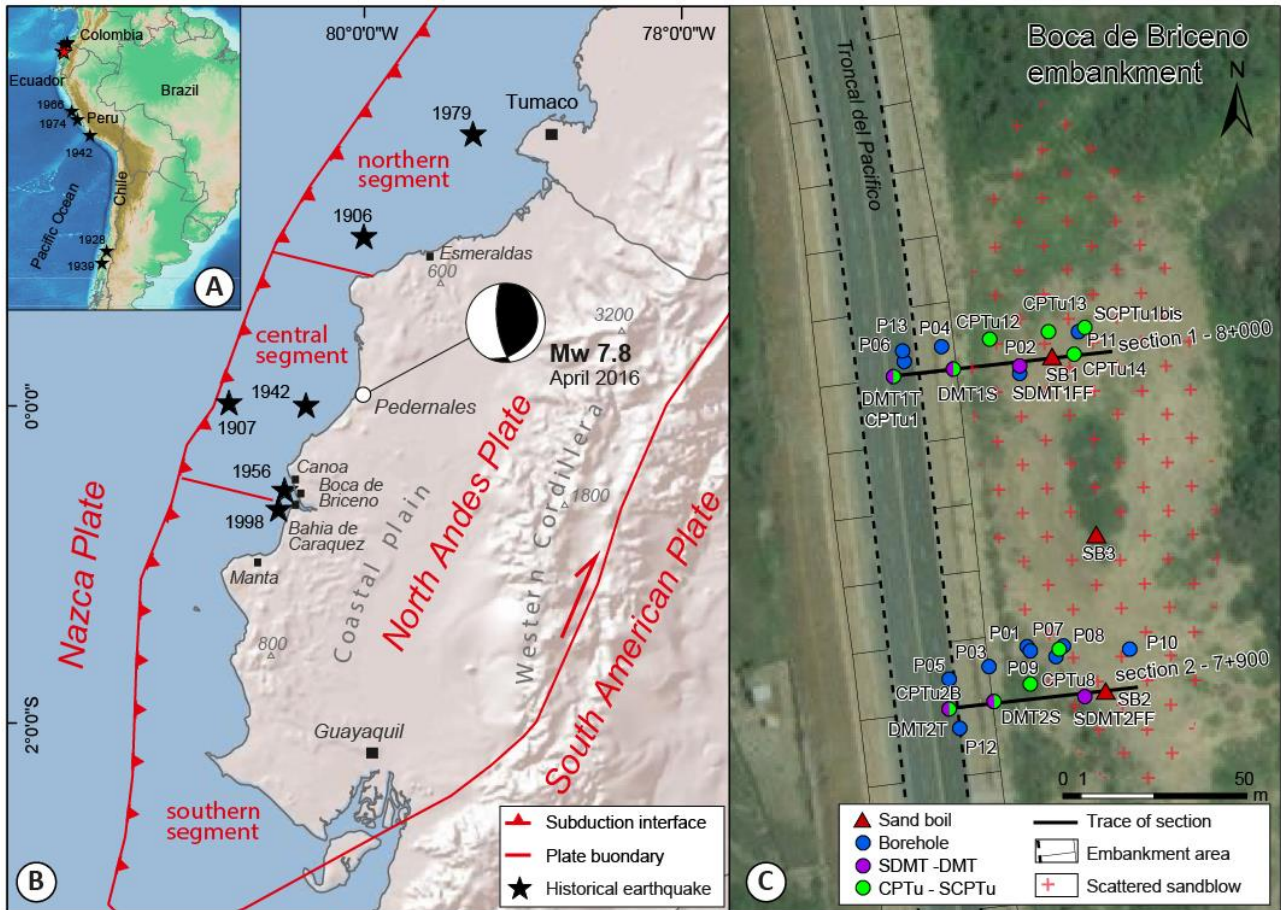
## 1. Introduction

Several liquefaction phenomena occurred as a consequence of a strong earthquake ( $M_w$ 7.8) of April 2016 along the central Pacific coastline of Ecuador (GEER-ACT, 2016; Chunga et al., 2017). The earthquake was located onshore, less than 10 km southeast of the city of Pedernales, with a hypocentral depth of 21 km, rupturing the central seismogenic segment of the South American subduction zone. In this area, the study of the liquefaction phenomena is particularly significant because frequent and very strong earthquakes are generated by megathrusts in a geological context characterized by continuous uplift and high sedimentation rate providing a complex stratigraphic architecture. In particular, the sediments involved in the liquefaction phenomena belong to the high-frequency sedimentary cycles related to the Quaternary climatic oscillations, which are extremely well recorded in the marine-continental successions. Moreover, the study of liquefaction effects is particularly relevant considering that these coastal areas contain urban centres, infrastructure and communication networks, that were recently the object of innovative mitigation strategies (Smith and Wissmann 2018, Vera-Grunauer et al. 2019, Amoroso et al. 2020a).

The aim of this research is to define the stratigraphic architecture of the shallow subsurface of the Boca de Briceño area in order to identify the source levels for liquefaction, using the texture and composition of sand boils compared with the buried sedimentary sequence. The study also may provide insights into ejection mechanisms in regions impacted by frequent earthquakes that triggered recurrent liquefaction (Giona Bucci et al., 2018; Maurer et al., 2019) and contribute in evaluating the success of a mitigation project carried out below a highway embankment in this area.

## 2. Geological setting

The study area is located on the coast of mainland Ecuador, a zone of intense crustal deformation due to the subduction of the Nazca oceanic plate beneath the South-American continental plate (Fig. 1). The subduction occurs along a N90°E direction at a rate of 58-78 mm/a (Trenkamp et al., 2002). The subduction induces a shortening perpendicular to the trench axis and, in turn, the expulsion of the north Andean block to the Northeast along the Guayaquil Caracas Megashear, with a rate of ~6 to 10 mm/a (Kellogg and Vega, 1995; Ego et al., 1996; Trenkamp et al., 2002). Recently, before the 2016 earthquake ( $M_w$  7.8), the Ecuadorian shoreline experienced strong megathrust earthquakes: in 1906 (estimated  $M_w$  8.8, 600-km long rupture area, one of the strongest earthquake registered on our planet), 1942 ( $M_w$  7.8), 1958 ( $M_w$  7.7), and 1979 ( $M_w$  8.2).



69

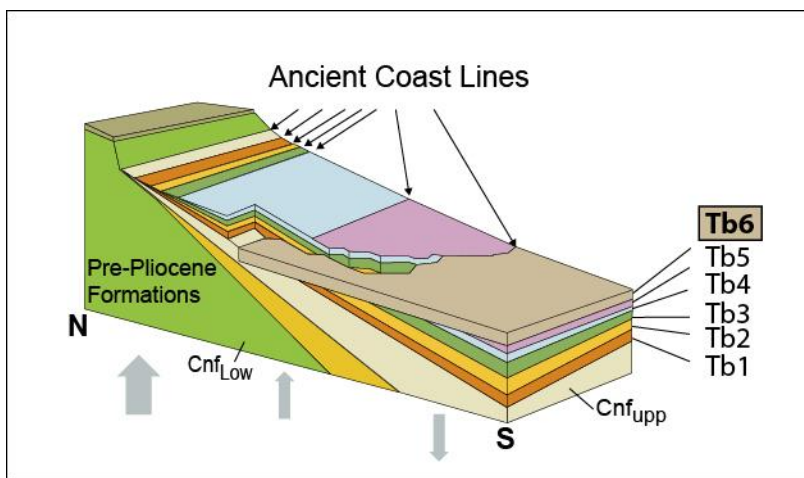
70 **Fig. 1** Location (A) and seismotectonic map (B) of the Briceño Bridge area in Ecuador with  
 71 indication of the historical earthquakes (modified after Amoroso et al., 2020 and Chunga et al.  
 72 2018). Study area with location of sand blows and boreholes (C).

73

74 The Colombia–Ecuador subduction trench is characterized by rapid sedimentation due to a tropical  
 75 climate and orographic rains on the western Andean slope caused by the prevailing Pacific winds.  
 76 The trench contains a thick sedimentary infill, up to 3 km-thick, probably due to recent turbidites  
 77 associated with hemipelagic sedimentation. The high sediment thickness along the subducting  
 78 margin seems to influence the large ruptures associated with great megathrust earthquakes. The  
 79 subduction of large volumes of sediments creates a sort of homogenous plate interface, which  
 80 allows the seismic ruptures to overcome the bathymetric barriers, propagating the trench-parallel  
 81 ruptures (Alvarez et al., 2017).

82 The Ecuadorian margin substratum consists of the oceanic North-Andean block accreted to the  
 83 Brazilian continental craton during the Cretaceous (Jaillard et al., 1997). The oceanic terranes are  
 84 made up of tholeiitic-andesitic basalts and pillow lavas associated with siliceous sediments (Piñon  
 85 Formation) overlain by intra-oceanic volcanic arc sequences (Cayo formation, Jaillard et al., 1995;  
 86 Reynaud et al., 1999).

87 The coastal area of Ecuador (Talara Arc) is actively uplifted along a concave subduction zone. The  
88 uplift is related to the eastward subduction of the aseismic Carnegie Ridge, which is part of the  
89 oceanic Nazca plate. The active subduction of the ridge is responsible for great lateral variations in  
90 deformation, seismicity, magmatism and sediment deposition along the margin (Gutscher et al.,  
91 1999; Collot et al., 2002). The uplift rate in the coastal area of Ecuador ranges between 0.10 and  
92 0.42 mm/a for the Late Quaternary (Pedoja et al., 2006). As a result of the rapid uplift, the coast is  
93 characterized by well-preserved, raised, marine terraces, called Tablazos, which show late Pliocene  
94 to Pleistocene high-frequency depositional sequences (Cantalamesa et al., 2001; Di Celma et al.,  
95 2002).



96  
97 **Fig. 2** Block diagram illustrating the Plio-Pleistocene stratigraphic architecture of costal Ecuador  
98 according to Cantalamessa and Di Celma (2004). CnF<sub>low</sub>: lower Canoa Formation, CnF<sub>upp</sub>: upper  
99 Canoa Formation. Tb: Cyclothems of the Tablazo Formation. The studied succession belongs to the  
100 Tb6 sequence.

101

102

### 103 2.1 The sedimentary sequence of the coastal margin

104 The combined effects of tectonic coastal uplift and Quaternary sea level fluctuations resulted in the  
105 formation of a series of raised marine terraces on the coastal stretch of mainland Ecuador. The  
106 Pliocene-Pleistocene coastal sequence was traditionally subdivided into the Canoa Formation and  
107 the Tablazo Formation (Sheppard, 1930). Di Celma et al. (2002) and Cantalamessa and Di Celma  
108 (2004) recognized up to four marine terraces in the area, while Pedoja et al. (2006) mapped up to  
109 five terraces. The significance of the terraces for the interpretation of the uplift rates of coastal  
110 Ecuador was stressed by Pedoja et al. (2006a, 2006b) and the cyclothem nature of these  
111 formations was described in detail by Di Celma et al. (2002), Cantalamessa and Di Celma (2004).  
112 According to Cantalamessa and Di Celma (2004), the sedimentary succession lies unconformably  
113 on pre-Pliocene deposits and reflects deposition in offshore, shoreface, and alluvial environments

114 (Fig. 2). The cyclothem consists of a deepening–shallowing upward facies association bounded by a  
115 ravinement surface, amalgamated with the preexisting sequence boundary. Each of the marine  
116 terraces formed during sea-level rise and highstand, and was progressively uplifted during a cycle  
117 of sea-level fluctuation. The terraces are composed of a wave-cut platform formed during the  
118 transgressive stage, covered by thin beach deposits consisting of sands, pebbles and shell fragments.  
119 The Canoa Formation lies unconformably over the Tosagua Formation (Early Miocene) and has  
120 been divided into two units with different deepening–shallowing facies associations, CnF<sub>low</sub> (late  
121 Pliocene) and CnF<sub>upp</sub> (Early Pleistocene), separated by an angular unconformity. The Tablazo  
122 Formation (Middle Pleistocene–Holocene) consists of at least six cyclothem characterized by a  
123 deepening–shallowing facies sequence. The cyclothem represent a single forced regressive  
124 sequence set.

125 Only in the last cyclothem (sequence Tb6, Fig. 2) the shallowing-upward part of the depositional  
126 sequence can be seen, differently from the lower cyclothem where the corresponding part of the  
127 sequence was eroded during the ravinement surface formation at each sequence boundary.  
128 Sequence Tb6 begins with a ravinement surface followed by a transgressive, deepening-upward  
129 shoreface succession, capped by a shallowing-upward shoreface to coastal-plain facies succession.  
130 In correspondence of the main fluvial entry points, the sequence is cut by valleys filled by estuarine  
131 sediments. The alluvial-estuarine deposits may contain Late Pleistocene–early Holocene continental  
132 vertebrate (Cantalamessa et al., 2001). The fluvial valleys, cut during sea level lowstands, were  
133 flooded and filled during the early phase of the Holocene transgression. As a whole, the  
134 depositional sequence seems to reflect the last cycle of sea-level fluctuation since MIS 5e, and  
135 represents the result of the sedimentation of the last 124 ka.

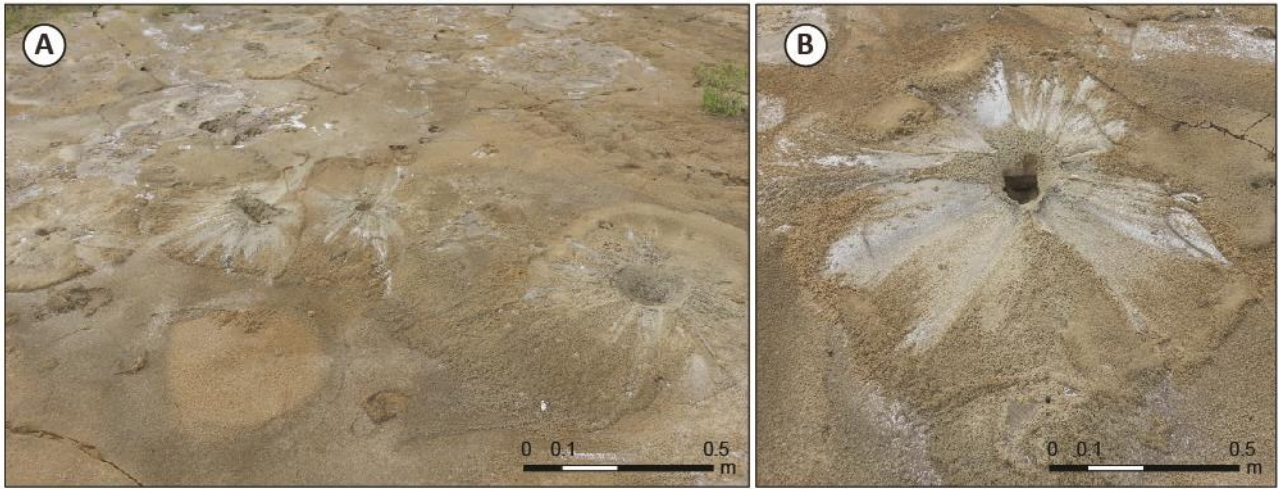
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## 137 *2.2 The Boca de Briceño area*

138 The area is characterized by Mio-Pleistocene turbidite deposits and Quaternary alluvial and marine  
139 terraces consisting of gravels, sand, silt and clay, highly variable in thickness and lateral extent, cut  
140 by the Rio Briceño valley. Detailed post-earthquake surveys were performed to detect the numerous  
141 site effects developed in the area, as well as along the Ecuadorean coast (GEER-ACT 2016, Chunga  
142 et al. 2017). In particular, liquefaction phenomena were observed and studied at the Briceño  
143 embankment, approximately 7 km from Canoa city and 112 km from the earthquake epicenter (Fig.  
144 1b). The estimated peak ground acceleration at the site was 0.4g (Ye et al., 2016, Beauval et al.,  
145 2017).

146 The earthquake shaking generated numerous sand boils in the alluvial plain (Fig. 1c), clustering in a  
147 wide elongated area next to the river mouth, a few hundreds of meters from the shoreline (Fig. 1c).

148 Sand boils were generally small, about 1 m across and a few centimetres high, and grew above a  
149 flat surface cut by mud cracks (Fig. 3).



150  
151 **Fig. 3** Sand boils in the Briceño Bridge area photographed after the main shock, a few months later  
152 (A), and detail of a sand volcano (B).

153  
154 As shown in Fig 1c, the sand boils are located in the area adjacent to the embankment, next to the  
155 bridge abutment, along the the Troncal de Pacifico Road. This infrastructure exhibited minimal  
156 damage due to the earthquake (GEER-ACT, 2016), likely as a result of a mitigation project to  
157 prevent liquefaction-induced failures (Smith and Wissmann 2018). Rammed aggregate pier®  
158 (RAP) ground improvement elements were used to reinforce foundation materials and to increase  
159 the stability of the sand deposits in the subsurface, which has been used successfully at similar sites  
160 in New Zealand (Wissmann et al., 2015 ; Wentz et al., 2015 ; Vauther in et al., 2017) and in Italy  
161 (Amoroso et al., 2020b).

162 In this context, an extensive geological and geotechnical site characterization campaign was  
163 performed mostly along two sections of the Briceño bridge embankment, with the aim of  
164 examining in depth the mechanisms involved in the liquefaction processes and evaluation of  
165 mitigation effectiveness (Smith and Wissmann, 2018; Amoroso et al., 2020a).

166

### 167 **3. Methods and sampling**

168

169 To reconstruct the stratigraphy of the area (Fig. 4), we based our observations on the complete  
170 dataset acquired during the mitigation project and subsequent post-earthquake investigations (Smith  
171 and Wissmann, 2018; Amoroso et al., 2020a). In particular we examined in detail cores from 13  
172 boreholes: five log cores (P07, P08, P09, P10, P11) to a depth of 6 m, five log cores 12 m deep (P02  
173 starting from the ground level and P03, P04, P05, P06 starting from the bridge embankment) and  
174 one core to a depth of 30 m (P01). The stratigraphic observations were supplemented by

175 geotechnical data consisting of standard penetration test (SPT), Atterberg limits, 16 piezocone tests  
176 (CPTu), 4 seismic piezocone tests (SCPTu), 5 flat dilatometer tests (DMT) and 2 seismic  
177 dilatometer tests (SDMT). The location of cores and other investigations is reported in Fig. 1c.  
178 Four boreholes (P07, P09, P10, P11) were sampled for textural (grain size) and compositional  
179 analyses (Fig. 4). The same textural and petrographic analyses were carried out on sand volcanoes  
180 from three different sites (samples SB1, SB2, SB3; with locations reported in Fig 1c).  
181 *Grain-Size Analyses.* We analyzed eighteen samples from cores P07, P09, P10, P11 at different  
182 depths and from sand blows (Table 1, Fig. 5). Grain-size analyses were performed on the  
183 Mastersizer 3000 Laser granulometry (Low Angle Laser Light Scattering) at laboratories of the  
184 DSCG of the University of Modena and Reggio Emilia. Organic matter was removed from 80 g of  
185 samples by hydrogen peroxide (H<sub>2</sub>O<sub>2</sub>); the samples were air dried and mechanically sieved for  
186 granulometric and compositional analyses. About 0.5 g of sample were transferred into a 250 ml  
187 beaker filled by deionized water. The suspension was lit by the low-intensity laser beam; particle-  
188 size distribution data were obtained under constant agitation in the measuring beaker. A refractive  
189 index of 1.52 for the laser radiation ( $\lambda = 750$  nm), an absorption coefficient of 0.1 and a Dispersal  
190 Refractive Index of 1.33 for the total range were used. For each sample five measurements were  
191 taken for three aliquots, then averaged. Index properties were estimated using the grain size  
192 distribution, by means of the Atterberg limits, fines content (FC) which represents percentage of  
193 particles finer than 0.075 mm; the diameters of the 60<sup>th</sup> (D<sub>60</sub>), 30<sup>th</sup> (D<sub>30</sub>), and 10<sup>th</sup> (D<sub>10</sub>) percentile of  
194 the granulometric curve; the coefficient of uniformity (U), given by the ratio between D<sub>60</sub> and D<sub>10</sub>;  
195 and the coefficient of curvature (C), function of D<sub>60</sub>, D<sub>30</sub>, and D<sub>10</sub>.  
196 *Compositional Analyses.* Point counting was performed on eleven samples under transmitted-light  
197 microscopy on the 0.125–0.250 mm fraction, according to the Gazzi-Dickinson method designed to  
198 minimize the dependence of the analysis on the grain size (Zuffa, 1985; Arribas and Tortosa, 2003).  
199 We distinguished 23 compositional categories reported in Table 2. Results are plotted in the  
200 traditional Q (quartz), F (feldspars), L (siliciclastic lithics) + C (carbonate) diagram (Fig. 6a) and  
201 are shown also in the Q+F, L, C plot (Fig 6b) that makes it possible to better differentiate the  
202 compositional fields in Quaternary sands, as discussed by Lugli et al. (2007).

203

## 204 **4. Results**

205

### 206 *4.1 The Boca de Briceño sedimentary sequence*

207 The studied sedimentary sequence can be divided into 5 main lithological units showing variable  
 208 thickness. These units, detected in both sections of the bridge embankment shown in Fig. 4, are  
 209 from the top to the bottom:

210 Unit 1, consisting of recent laminated silt and clayey silt with subordinate sandy layers, from the  
 211 ground level to a depth ranging from 1.35 to 3.50 m; the unit locally fills paleochannels and may  
 212 reach the depth of 5 m (section 1).

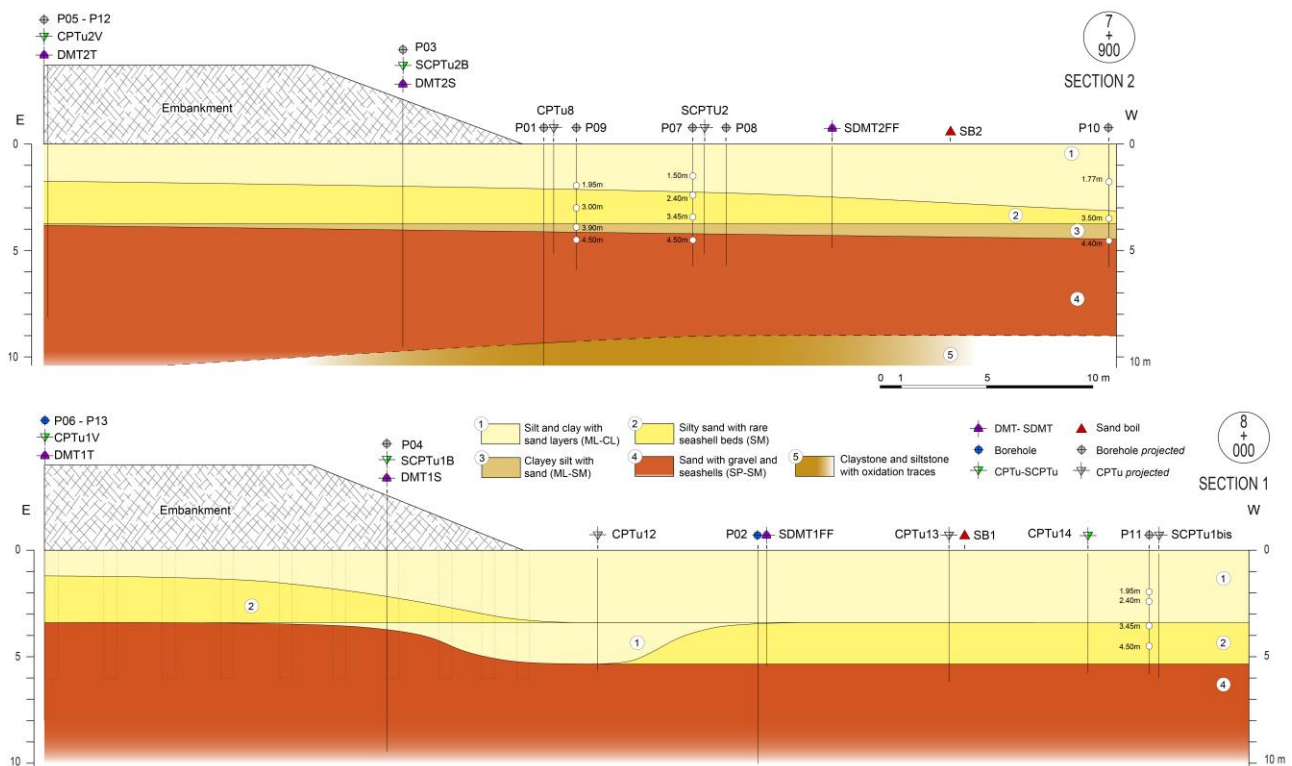
213 Unit 2, consisting of silty sands with rare seashell beds, with variable thickness within the studied  
 214 area; the top of the unit ranges from 1.35 to 3.5 m depth, and its base from 3.8 to 5.50 m depth.

215 Unit 3 is very thin (maximum 1 m thick) and discontinuous, made up of clayey silt with subordinate  
 216 sands, and it has been recognized only in the southern area (section 2 in Fig. 4) at the depth of 4 m.

217 Unit 4 consists mainly of coarse-grained sands and minor pebbles with abundant seashell beds. The  
 218 top of the unit ranges from 3.8 to 5.50 m depth and the bottom from 9.00 m (P01) to more than 12  
 219 m depth (P02 hole bottom).

220 Unit 5, consists of compacted silty and clayey sediments with subordinate silty sands and  
 221 widespread oxidation traces. The top of the unit is detected at a depth varying from 9.00 m to more  
 222 than 12 m, and it extends down to a depth of 28.65 m (P01 hole bottom).

223



224

225 **Fig. 4** Stratigraphic scheme of the successions involved in the liquefaction in the Briceño Bridge  
 226 area showing the boreholes, the geotechnical tests (modified from Amoroso et al., 2020b) and the  
 227 reconstructed lithological units across two sections (section 1 and section 2; see Fig. 1 for location).

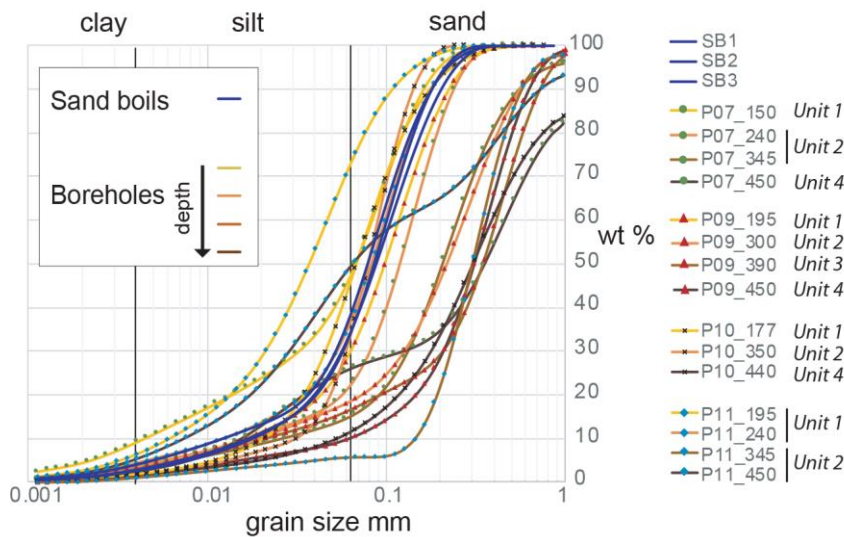
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229 4.3 Grain-size

230

231 The grain-size of the examined core samples ranges from almost pure sand to sandy silt (Fig. 5); the  
 232 silt fraction varies from 10 to 60%, but the amount of clay is always less than 10%. An increase in  
 233 grain size is observed with depth: finer samples characterize the shallow portion of the cores (at 1.5  
 234 to about 2 m depth below the ground level). From 2 to 4.5 m sands are fine to medium-grained (in  
 235 two samples a coarse-grained fraction is also present) and the silty fraction is less than 40% (with  
 236 the exception of sample P11\_450, which is characterized by a higher amount of silt, about 50%).

237 The sand volcanoes are made up of fine sands, and the three examined samples perfectly overlap  
 238 despite belonging to different liquefaction sites. The amount of silt is around 30% and clay is less  
 239 than 5%.



240

241 **Fig. 5** Cumulative grain-size distributions of examined samples from cores at different depths and  
 242 from sand blows (in blue).

243

244 The grain size analyses and the calculated index properties were then used to provide the USCS  
 245 classification (ASTM D2487-11, 2011), reported in Table 1. Samples from shallow unit 1 are sandy  
 246 silt (ML), whereas samples from deeper units 2 and 3 are silty sand (SM). The index properties  
 247 (Table 1) indicate a similar high fines content in both the silty sand (SM) layers ( $FC \approx 17-53\%$ ), and  
 248 in the sand blows ( $FC \approx 43-48\%$ ). The samples from the boreholes and the sand blows are well-  
 249 graded (i.e., they contain particles with a wide range of sizes), as shown by the coefficients of  
 250 curvature C and uniformity U. Atterberg limits confirmed that all the samples are non-plastic.

| Samples | Description/Depth               | FC (%) | D <sub>60</sub> (mm) | D <sub>30</sub> (mm) | D <sub>10</sub> (mm) | U    | C   | USCS classification                  |
|---------|---------------------------------|--------|----------------------|----------------------|----------------------|------|-----|--------------------------------------|
| P07_150 | Section 2 - Borehole P07 1.50 m | 55.64  | 0.0832               | 0.0324               | 0.0045               | 18.6 | 2.8 | Sandy silt (ML)                      |
| P07_240 | Section 2 - Borehole P07 2.40 m | 27.41  | 0.1401               | 0.0814               | 0.0177               | 7.9  | 2.7 | Silty sand (SM)                      |
| P07_345 | Section 2 - Borehole P07 3.45 m | 17.07  | 0.2502               | 0.1322               | 0.0263               | 9.5  | 2.7 | Silty sand (SM)                      |
| P07_450 | Section 2 - Borehole P07 4.50 m | 27.24  | 0.4594               | 0.1245               | 0.0155               | 29.6 | 2.2 | Silty sand (SM)                      |
| P09_195 | Section 2 - Borehole P09 1.95 m | 37.22  | 0.1182               | 0.0634               | 0.0163               | 7.3  | 2.1 | Silty sand (SM)                      |
| P09_300 | Section 2 - Borehole P09 3.00 m | 20.52  | 0.2692               | 0.1256               | 0.0195               | 13.8 | 3.0 | Silty sand (SM)                      |
| P09_390 | Section 2 - Borehole P09 3.90 m | 18.24  | 0.4101               | 0.2060               | 0.0210               | 19.5 | 4.9 | Silty sand (SM)                      |
| P09_450 | Section 2 - Borehole P09 4.50 m | 11.62  | 0.3621               | 0.2072               | 0.0616               | 5.9  | 1.9 | Poorly graded sand with silt (SP-SM) |
| P10_177 | Section 2 - Borehole P10 1.77 m | 56.00  | 0.0820               | 0.0457               | 0.0207               | 4.0  | 1.2 | Sandy silt (ML)                      |
| P10_350 | Section 2 - Borehole P10 3.50 m | 46.69  | 0.0902               | 0.0597               | 0.0312               | 2.9  | 1.3 | Silty sand (SM)                      |
| P10_440 | Section 2 - Borehole P10 4.40 m | 13.60  | 0.3867               | 0.1767               | 0.0527               | 7.3  | 1.5 | Silty sand (SM)                      |
| P11_195 | Section 1 - Borehole P11 1.95 m | 80.03  | 0.0466               | 0.0210               | 0.0062               | 7.6  | 1.5 | Silt with sand (ML)                  |
| P11_240 | Section 1 - Borehole P11 2.40 m | 45.51  | 0.0983               | 0.0530               | 0.0124               | 8.0  | 2.3 | Silty sand (SM)                      |
| P11_345 | Section 1 - Borehole P11 3.45 m | 5.73   | 0.3458               | 0.2300               | 0.1450               | 2.4  | 1.1 | Poorly graded sand with silt (SP-SM) |
| P11_450 | Section 1 - Borehole P11 4.50 m | 53.34  | 0.1213               | 0.0286               | 0.0074               | 16.5 | 0.9 | Sandy silt (ML)                      |
| SB1     | 2016 sand boil                  | 48.18  | 0.0936               | 0.0520               | 0.0122               | 7.7  | 2.4 | Silty sand (SM)                      |
| SB2     | 2016 sand boil                  | 43.42  | 0.1008               | 0.0571               | 0.0168               | 6.0  | 1.9 | Silty sand (SM)                      |
| SB3     | 2016 sand boil                  | 42.80  | 0.1059               | 0.0562               | 0.0178               | 5.9  | 1.7 | Silty sand (SM)                      |

251

252 **Table 1.** Index properties of the analyzed samples: FC is the fines content; D<sub>60</sub>, D<sub>30</sub>, and D<sub>10</sub> are the  
 253 diameters of the 60<sup>th</sup>, 30<sup>th</sup>, and 10<sup>th</sup> percentiles of the grain size distribution; U is the coefficient of  
 254 uniformity; C is the coefficient of curvature.

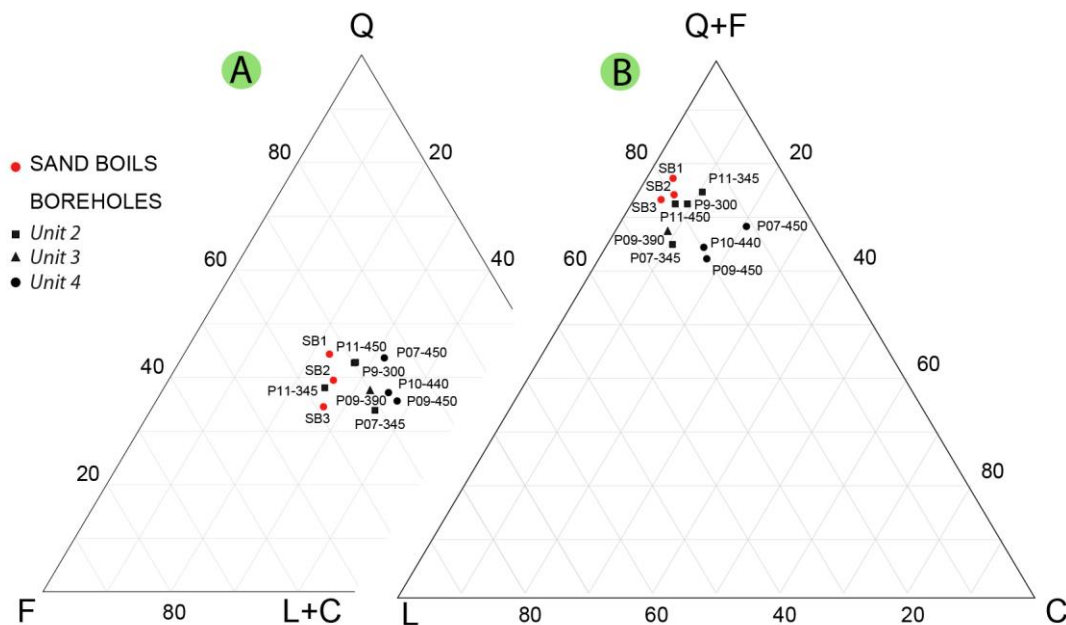
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256 *4.4 Composition of sands*

257 The results from the modal analyses are reported in Table 2 and in the ternary diagrams of Fig. 6.

258 The petrography under the optical microscope is shown in Fig. 7.

259



260

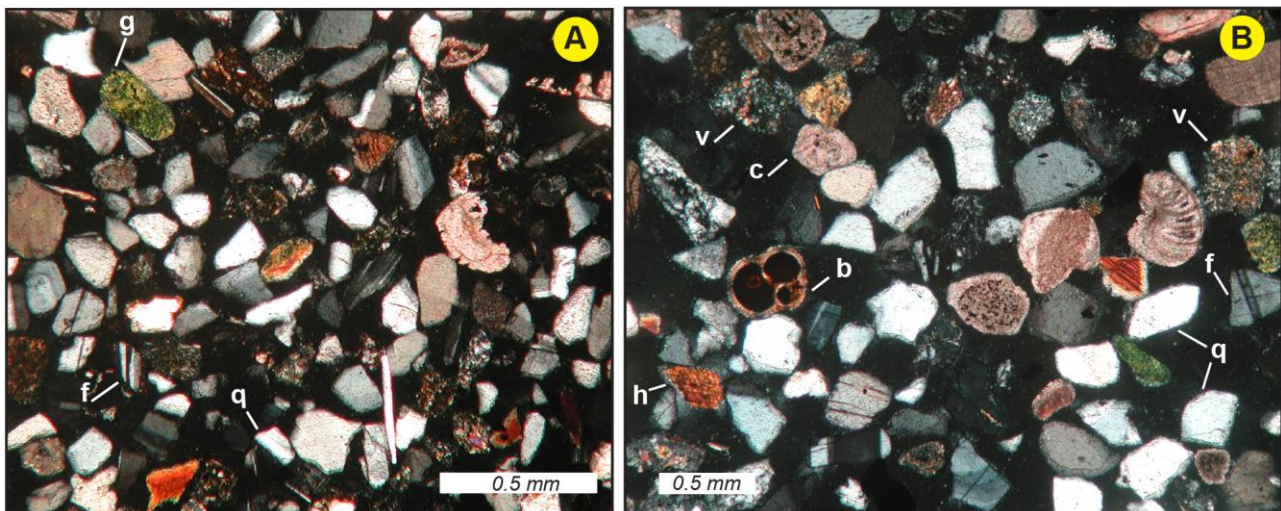
261 **Fig. 6** Ternary diagrams Q,F, L+C and Q+F, L, C showing the composition of examined sands from  
262 cores (numbers refer to depth) and from liquefied sand boils (in red). Q, total quartz; F, total  
263 feldspars; L, siliciclastic lithic fragments; C, carbonate fragments.  
264

265 In general, sands from the cores are made up of quartz (single crystal and polycrystalline) ranging  
266 from 28.0 to 37.3% of the bulk rock. Total feldspars range from 20 to 33% and consist largely of  
267 plagioclase and subordinately K-feldspar (orthoclase and microcline). Both quartz and feldspar  
268 grains are angular. Siliciclastic lithic fragments are made up primarily of volcanites (with  
269 microcrystalline groundmass with feldspar phenocrysts), spilites and serpentinites. Low-grade  
270 metamorphic rocks are minor components consisting of mica schist and phyllades. Sedimentary  
271 rocks include siltstones and shale. Siliciclastic lithics account for 9 to 21% of the whole rock.

272 Carbonate grains (6 to 16.3%) are made of bioclasts (benthic foraminifera, algae) (Fig. 7b), calcite  
273 spar and micritic grains. The amount of bioclasts is higher in the deeper samples (at depth of 4.5 m)  
274 and significantly decreases in the shallower samples (from 3.9 to 3.0 m depth).

275 Other significant components are micas, biotite, muscovite and chlorite, amphibole (mainly  
276 hornblende, green and brown), pyroxene and garnet. Glauconite is present in small amounts (less  
277 than 1%) in several samples. Opaque minerals (pyrite) and Fe-oxides are subordinate components.

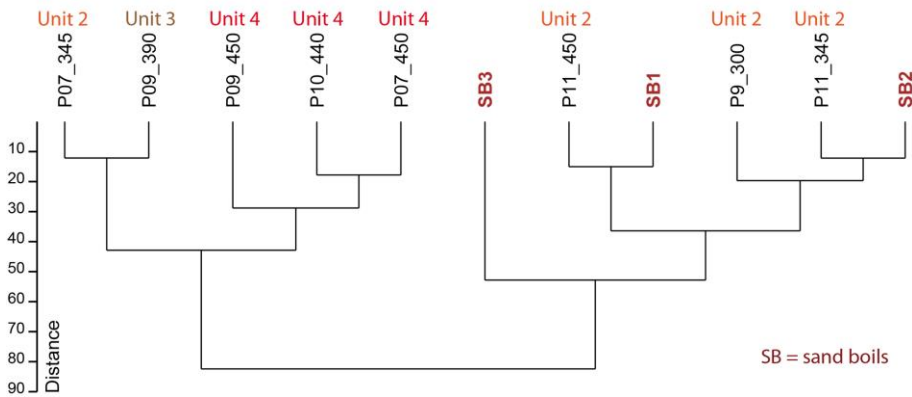
278 In all the studied sands, grains are angular to subangular.



279  
280 **Fig. 7** Photomicrographs of the examined sands. A) sand blow (sample SB1) and B) core sample  
281 (P09\_450), showing the main components, q: quartz, f: feldspars, b: bioclasts, c. calcite spar, v.  
282 volcanics, h. hornblende, g. glauconite. Transmitted light, crossed polars.  
283

284 The composition of the sands indicate provenance from the erosion of the metamorphic/magmatic  
285 basement and volcanic rocks. Subordinate contributions are from sedimentary units (largely  
286 Miocene turbidite successions), in turn recycling basement lithotypes.

287 Samples from sand blows have a quite homogeneous composition with the same components  
 288 described for the core sands. Mainly based on the low amounts of carbonates, which consist largely  
 289 of bioclasts, the ejected sands show similarities with the shallower sands of unit 2. The similarity  
 290 among samples is assessed by the Ward distribution, calculated using all the petrographic  
 291 parameters (Fig. 8).



293  
 294 **Fig. 8** Dendrogram showing the distribution of samples calculated using all the petrographic  
 295 parameters. Ward's method. Similarity index: Euclidean.

296

|   |                                | Boreholes |         |         |         |         |         |         |         | Sand boils |      |      |
|---|--------------------------------|-----------|---------|---------|---------|---------|---------|---------|---------|------------|------|------|
|   |                                | P07_345   | P07_450 | P09_300 | P09_390 | P09_450 | P10_440 | P11_345 | P11_450 | SB1        | SB2  | SB3  |
| Q | Quartz single crystal          | 27,3      | 33,3    | 33,3    | 27,0    | 25,3    | 29,3    | 31,3    | 35,0    | 35,0       | 31,7 | 28,7 |
|   | Quartz polycrystalline         | 1,0       | 1,7     | 1,3     | 2,3     | 1,0     | 2,0     | 1,0     | 1,3     | 2,7        | 1,7  | 3,0  |
|   | Quartz in Rock fragment (r.f.) | 0,3       | 0,3     | 1,0     | 1,0     | 1,7     | 0,0     | 1,7     | 1,0     | 1,3        | 0,3  | 0,7  |
| F | K-feldspar single crystal      | 4,7       | 3,7     | 8,7     | 4,0     | 6,7     | 6,0     | 11,0    | 3,3     | 7,0        | 10,0 | 4,3  |
|   | K-feldspar in r.f.             | 0,3       | 0,0     | 0,0     | 0,3     | 0,0     | 0,0     | 0,0     | 0,0     | 0,0        | 0,3  | 0,0  |
|   | Plagioclase single crystal     | 20,3      | 16,3    | 16,3    | 19,3    | 14,3    | 17,0    | 20,7    | 22,7    | 21,7       | 19,0 | 31,3 |
|   | Plagioclase in r. f.           | 1,0       | 0,0     | 0,0     | 0,7     | 0,0     | 0,0     | 1,3     | 0,0     | 0,3        | 0,3  | 0,7  |
| L | Metamorphite                   | 1,7       | 1,0     | 1,0     | 0,0     | 0,7     | 1,0     | 0,7     | 1,3     | 2,7        | 2,0  | 1,0  |
|   | Volcanite                      | 8,0       | 5,0     | 7,0     | 8,7     | 10,0    | 6,0     | 5,0     | 7,0     | 9,3        | 6,3  | 12,0 |
|   | Spilite                        | 2,0       | 0,7     | 1,3     | 1,3     | 0,3     | 0,7     | 2,3     | 2,3     | 1,0        | 1,3  | 2,7  |
|   | Serpentinite                   | 1,7       | 0,0     | 0,7     | 0,3     | 1,0     | 0,0     | 0,0     | 0,7     | 1,7        | 1,0  | 1,0  |
|   | Siltite                        | 3,7       | 1,7     | 0,7     | 2,3     | 1,0     | 3,7     | 1,7     | 3,0     | 0,3        | 3,3  | 1,7  |
|   | Shale                          | 4,0       | 1,0     | 5,0     | 7,0     | 3,3     | 5,7     | 4,0     | 3,7     | 1,3        | 3,0  | 2,7  |
|   | Calcite spar                   | 0,3       | 1,7     | 1,7     | 0,7     | 1,7     | 1,3     | 3,3     | 0,7     | 0,3        | 1,7  | 0,3  |
| C | Micrite                        | 1,3       | 1,0     | 3,3     | 1,3     | 2,3     | 1,0     | 2,0     | 1,0     | 1,0        | 0,3  | 0,7  |
|   | Bioclast                       | 7,0       | 13,7    | 2,3     | 4,7     | 9,7     | 10,7    | 3,7     | 4,3     | 2,3        | 3,0  | 3,0  |
|   | Mica and Chlorite              | 2,7       | 7,3     | 7,0     | 2,3     | 7,3     | 4,7     | 3,7     | 2,3     | 3,3        | 7,0  | 3,3  |
|   | Heavy mineral (unspecified)    | 2,3       | 2,3     | 1,0     | 2,7     | 3,0     | 2,0     | 1,0     | 1,3     | 1,7        | 1,7  | 0,3  |
|   | Heavy mineral (anfíbol)        | 4,3       | 3,0     | 3,0     | 4,3     | 5,0     | 1,3     | 2,3     | 3,0     | 4,3        | 1,7  | 1,0  |
|   | Glauconite                     | 1,0       | 0,0     | 0,3     | 0,3     | 0,0     | 1,0     | 0,3     | 0,3     | 0,3        | 0,3  | 0,7  |
|   | Fe-oxide                       | 2,0       | 0,7     | 2,7     | 2,3     | 0,0     | 1,3     | 0,0     | 2,3     | 0,7        | 1,3  | 0,0  |
|   | Opaque                         | 2,3       | 4,7     | 1,7     | 5,0     | 4,7     | 3,7     | 1,3     | 2,0     | 1,3        | 1,3  | 0,0  |
|   | Undetermined                   | 0,7       | 1,0     | 0,7     | 2,0     | 1,0     | 1,7     | 1,7     | 1,3     | 0,3        | 1,3  | 1,0  |
|   |                                | 100%      | 100%    | 100%    | 100%    | 100%    | 100%    | 100%    | 100%    | 100%       | 100% | 100% |

297  
 298 **Table 2** Compositional modal analyses of examined sands (r.f., rock fragment). Composition is  
 299 determined based on transmitted-light spectroscopy of the 125–250 mm fraction.

300

## 301 5. Discussion

302

### 303 5.1 Interpretation of the cored sequence

304 The data from the 13 cores and from the geotechnical tests support the reconstruction of a detailed  
305 stratigraphic scheme of Quaternary alluvial-marine sediments in the area and, in particular, of the  
306 upper succession (from 0 to 5 m deep) in which the liquefiable layers are located (Fig. 4). Using the  
307 described lithological characteristics and the sedimentary features recognizable from core pictures,  
308 we may infer the following depositional environments:

- 309 - continental, fluvial-estuarine, for unit 1 and unit 5,
- 310 - marine to transitional fluvial, relatively-low energy, for units 2 and 3,
- 311 - marine, relatively-high energy, for unit 4.

312 Using as a reference the facies analyses of Di Celma et al. (2002), the studied sequence can be  
313 attributed to the shallowing-upward segment of the last cyclothem, the sequence Tb6 of the  
314 depositional model of Cantalamessa and Di Celma (2004).

315 The relatively large thickness of the continental deposits in the lower part of the sequence, unit 5,  
316 which is at least 20 m-thick, suggests that this segment may represent the continental infill of the  
317 fluvial paleo-valley of the Briceño River. The paleo-valley would have been cut during the sea level  
318 lowstand corresponding to the Last Glacial Maximum. The valley was then flooded and filled  
319 during the early phase of the Holocene transgression. The transition between units 4 and 5 may  
320 represent the ravinement surface followed by a transgressive shoreface succession (unit 4). The  
321 coarser marine sands of unit 4 may represent the exposed upper shoreface, and the following finer  
322 marine sands of unit 2 would correspond to the shoreface environment migrating inland. Unit 3 may  
323 represent the transitional marine-fluvial-estuarine facies. The topmost continental influx of unit 1  
324 would indicate the last evolution of the sequence during the high stand, producing the final  
325 regressive system tract made up of fluvial-estuarine mainly argillaceous sediments of the present-  
326 day Briceño River.

327

### 328 *5.2 The source layer identification*

329 The petrographic composition of the sands allows us to discriminate the studied lithological units.  
330 Sands of unit 4 are significantly richer in bioclasts and carbonate fragments relative to those of unit  
331 2. The petrography of the liquefied sands that ejected to the surface as sand boils, compared with  
332 that of buried sands, provides an important constraint in the recognition of the source layer. Based  
333 on the compositional affinity, in particular the low amount of bioclasts and carbonate grains, as  
334 shown by the Q+F, L, C ternary diagram (Fig. 6B), the sand boils were probably ejected from the  
335 shallow silty sand level of unit 2, whereas the deeper coarser sands of unit 4 were not affected. The  
336 affinity between the ejected sands and those of unit 2 is also confirmed considering the whole  
337 petrographic composition illustrated in the Ward diagram (Fig. 8).

338 The grain-size results also support the petrographic data in attributing the ejected sands to unit 2.  
339 Although the grain-size alone can not provide precise indications of the source layer, in this case the  
340 deeper sands of unit 4, which are coarser than those of the sand boils, can not be the source layer  
341 even considering segregation processes during ejection. The attribution of the source layer for  
342 liquefaction to unit 2 is in agreement with the geotechnical assessment performed by Smith and  
343 Wissmann (2018) and Vera-Grunauer et al. (2019).

344 In general, this study seems to corroborate previous findings that earthquake-induced liquefaction  
345 phenomena are not restricted to clean sands and well-sorted deposits, but may affect sand layers  
346 with significant amount of non-plastic silt, as recently recognized in liquefied sands in the Po plain  
347 (Italy; Fontana et al., 2015, 2019; Amoroso et al. 2020b).

348 The dependence of liquefaction susceptibility with particle shape and roundness has been discussed  
349 in the literature (Garga and McKay, 1984; Vaid et al, 1985; Hird and Hassona, 1990; Ishihara 1993;  
350 Ashour and Norris, 1999; Ashmawy et al., 2003). In our case we observe a distinct angular shape of  
351 the grains suggesting that, as discussed by Ashmawy et al. (2003) this parameter is not necessarily  
352 an influencing factor for liquefaction, which depends primarily on the sediment texture, fabric and  
353 porosity.

354

## 355 **6. Conclusions**

356

357 • The study of the sands ejected at Rio Briceño valley (Ecuador) during the Mw 7.8 earthquake  
358 of April 2016 and the comparison with buried alluvial-marine Quaternary sediments, provided us  
359 with clues about the source layers identification.

360 • The composition and fabric characteristics, such as grain-size distribution, indicate that  
361 liquefaction processes affected mainly sand layers at depth of 2-4.5 m, and a relatively shallow  
362 source for the blowouts. The deeper coarser marine sands, characterized by higher amounts of  
363 carbonate grains, mainly bioclasts, were not affected by liquefaction.

364 • This study seems to corroborate previous findings that earthquake-induced liquefaction  
365 phenomena are not restricted to clean sands and well-sorted deposits, but may affect sand layers  
366 with significant amount of non-plastic silt.

367

368

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