

This is a pre print version of the following article:

Liquefaction source layer for sand blows induced by the 2016 megathrust earthquake (Mw 7.8) in Ecuador (Boca de Briceño) / Salocchi, Aura C.; Minarelli, Luca; Lugli, Stefano; Amoroso, Sara; Rollins, Kyle M.; Fontana, Daniela. - In: JOURNAL OF SOUTH AMERICAN EARTH SCIENCES. - ISSN 0895-9811. - 103:(2020), pp. 1-10. [10.1016/j.jsames.2020.102737]

Terms of use:

The terms and conditions for the reuse of this version of the manuscript are specified in the publishing policy. For all terms of use and more information see the publisher's website.

09/11/2024 00:14

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

Aura C. Salocchi^a, Luca Minarelli^b, Stefano Lugli^a, Sara Amoroso^{b, c}, Kyle M. Rollins^d, Daniela Fontana^{a*}

^a Department of Chemical and Geological Sciences, University of Modena and Reggio Emilia, 41125 Modena, Italy

^b Istituto Nazionale di Geofisica e Vulcanologia, 67100 L'Aquila, Italy.

^c Department of Engineering and Geology, University of Chieti-Pescara, 65129 Pescara, Italy

^d Department of Civil and Environmental Engineering, Brigham Young University, UT 84602, USA.

* corresponding author, daniela.fontana@unimore.it

Abstract

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

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

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).

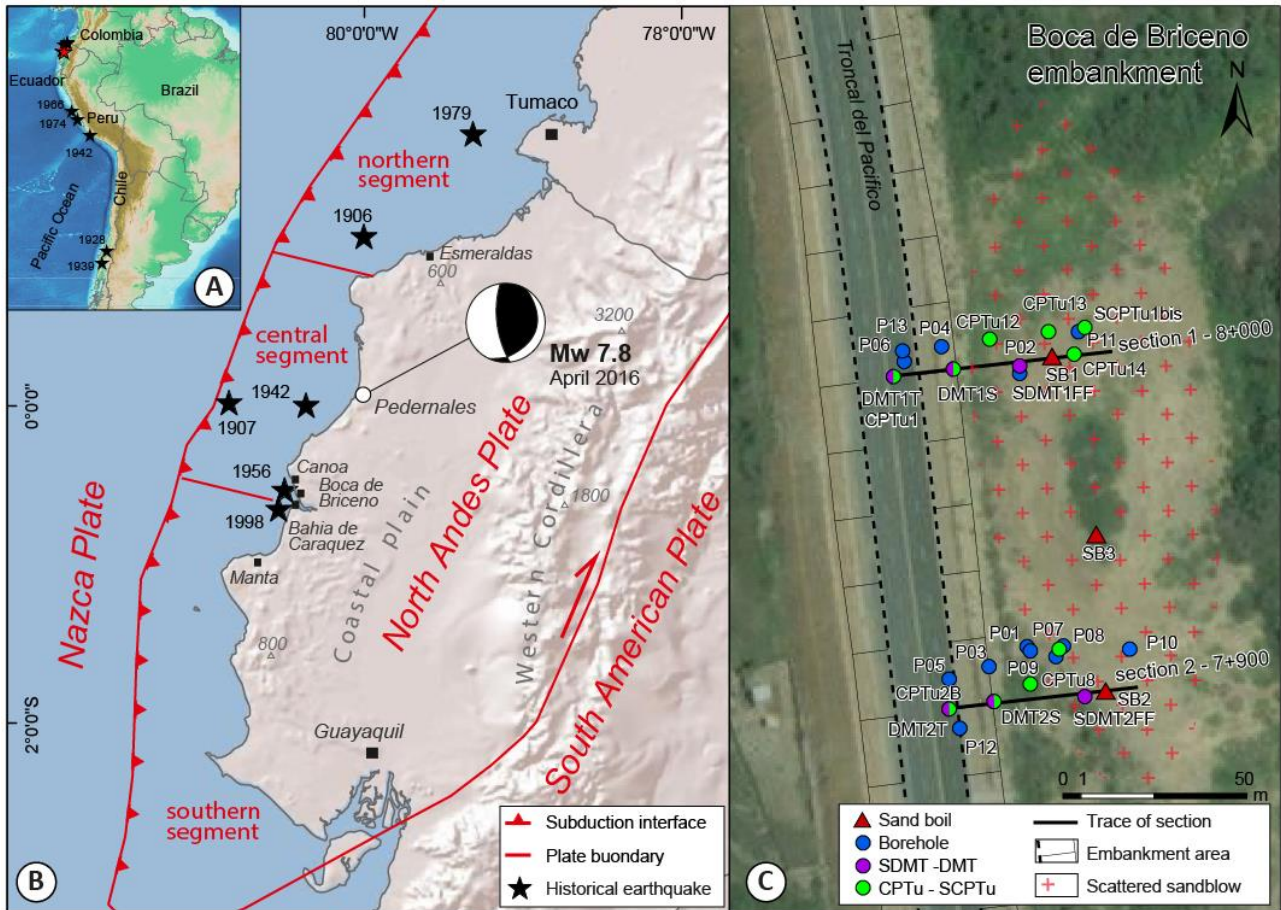
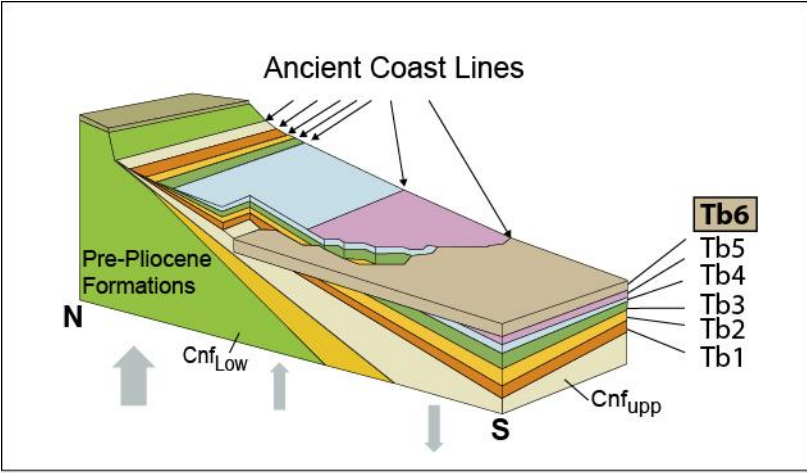


Fig. 1 Location (A) and seismotectonic map (B) of the Briceño Bridge area in Ecuador with indication of the historical earthquakes (modified after Amoroso et al., 2020 and Chunga et al. 2018). Study area with location of sand blows and boreholes (C).

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

The Ecuadorian margin substratum consists of the oceanic North-Andean block accreted to the Brazilian continental craton during the Cretaceous (Jaillard et al., 1997). The oceanic terranes are made up of tholeiitic-andesitic basalts and pillow lavas associated with siliceous sediments (Piñon Formation) overlain by intra-oceanic volcanic arc sequences (Cayo formation, Jaillard et al., 1995; 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 (Cantalamessa 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_{low}: lower Canoa Formation, CnF_{upp}: 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_{low} (late
121 Pliocene) and CnF_{upp} (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.

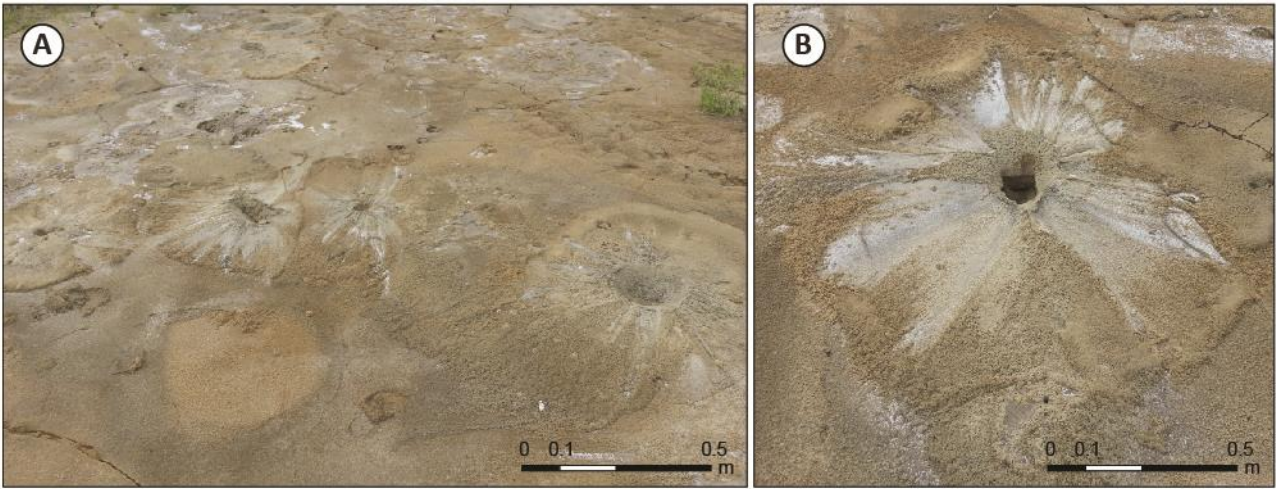
136

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

geotechnical data consisting of standard penetration test (SPT), Atterberg limits, 16 piezocone tests (CPTu), 4 seismic piezocone tests (SCPTu), 5 flat dilatometer tests (DMT) and 2 seismic dilatometer tests (SDMT). The location of cores and other investigations is reported in Fig. 1c. Four boreholes (P07, P09, P10, P11) were sampled for textural (grain size) and compositional analyses (Fig. 4). The same textural and petrographic analyses were carried out on sand volcanoes from three different sites (samples SB1, SB2, SB3; with locations reported in Fig 1c).

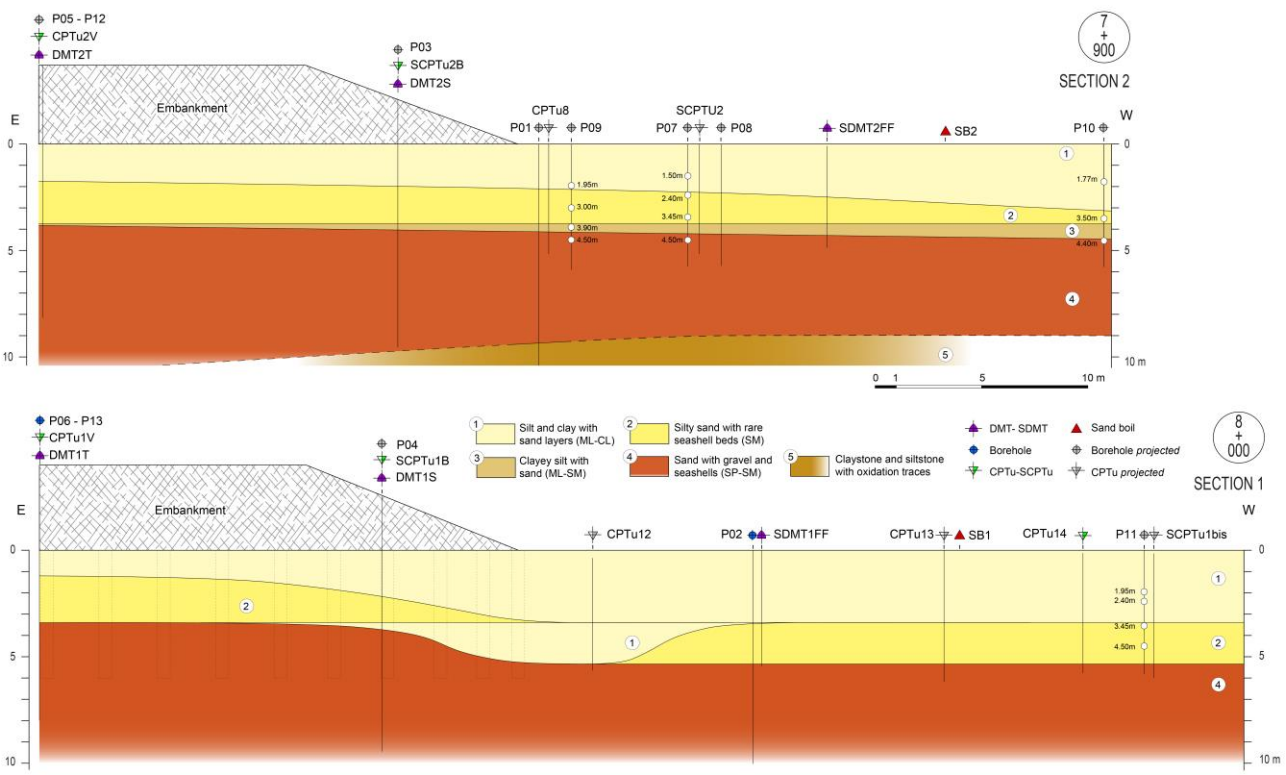
Grain-Size Analyses. We analyzed eighteen samples from cores P07, P09, P10, P11 at different depths and from sand blows (Table 1, Fig. 5). Grain-size analyses were performed on the Mastersizer 3000 Laser granulometry (Low Angle Laser Light Scattering) at laboratories of the DSCG of the University of Modena and Reggio Emilia. Organic matter was removed from 80 g of samples by hydrogen peroxide (H₂O₂); the samples were air dried and mechanically sieved for granulometric and compositional analyses. About 0.5 g of sample were transferred into a 250 ml beaker filled by deionized water. The suspension was lit by the low-intensity laser beam; particle-size distribution data were obtained under constant agitation in the measuring beaker. A refractive index of 1.52 for the laser radiation ($\lambda = 750$ nm), an absorption coefficient of 0.1 and a Dispersal Refractive Index of 1.33 for the total range were used. For each sample five measurements were taken for three aliquots, then averaged. Index properties were estimated using the grain size distribution, by means of the Atterberg limits, fines content (FC) which represents percentage of particles finer than 0.075 mm; the diameters of the 60th (D₆₀), 30th (D₃₀), and 10th (D₁₀) percentile of the granulometric curve; the coefficient of uniformity (U), given by the ratio between D₆₀ and D₁₀; and the coefficient of curvature (C), function of D₆₀, D₃₀, and D₁₀.

Compositional Analyses. Point counting was performed on eleven samples under transmitted-light microscopy on the 0.125–0.250 mm fraction, according to the Gazzi-Dickinson method designed to minimize the dependence of the analysis on the grain size (Zuffa, 1985; Arribas and Tortosa, 2003). We distinguished 23 compositional categories reported in Table 2. Results are plotted in the traditional Q (quartz), F (feldspars), L (siliciclastic lithics) + C (carbonate) diagram (Fig. 6a) and are shown also in the Q+F, L, C plot (Fig 6b) that makes it possible to better differentiate the compositional fields in Quaternary sands, as discussed by Lugli et al. (2007).

4. Results

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



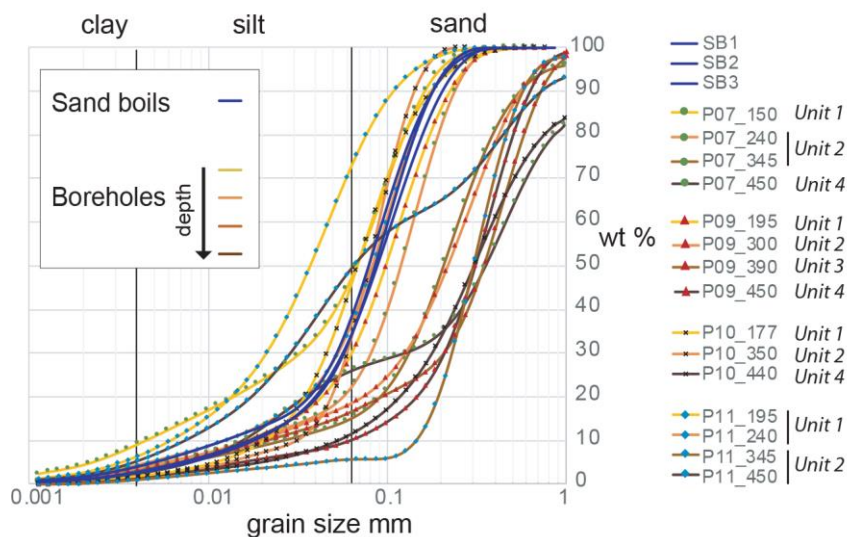
224
 225 **Fig. 4** Stratigraphic scheme of the successions involved in the liquefaction in the Briceño Bridge
 226 area showing the boreholes, the geotechnical tests (modified from Amoroso et al., 2020b) and the
 227 reconstructed lithological units across two sections (section 1 and section 2; see Fig. 1 for location).
 228

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

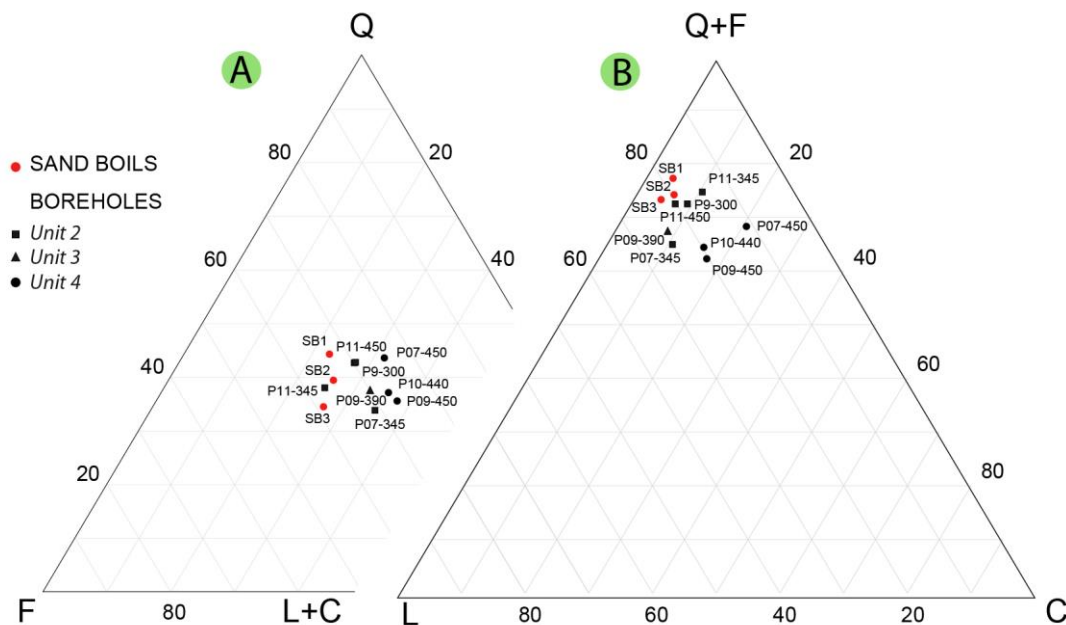
245 The grain size analyses and the calculated index properties were then used to provide the USCS
246 classification (ASTM D2487-11, 2011), reported in Table 1. Samples from shallow unit 1 are sandy
247 silt (ML), whereas samples from deeper units 2 and 3 are silty sand (SM). The index properties
248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

Samples	Description/Depth	FC (%)	D ₆₀ (mm)	D ₃₀ (mm)	D ₁₀ (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)

Table 1. Index properties of the analyzed samples: FC is the fines content; D₆₀, D₃₀, and D₁₀ are the diameters of the 60th, 30th, and 10th percentiles of the grain size distribution; U is the coefficient of uniformity; C is the coefficient of curvature.

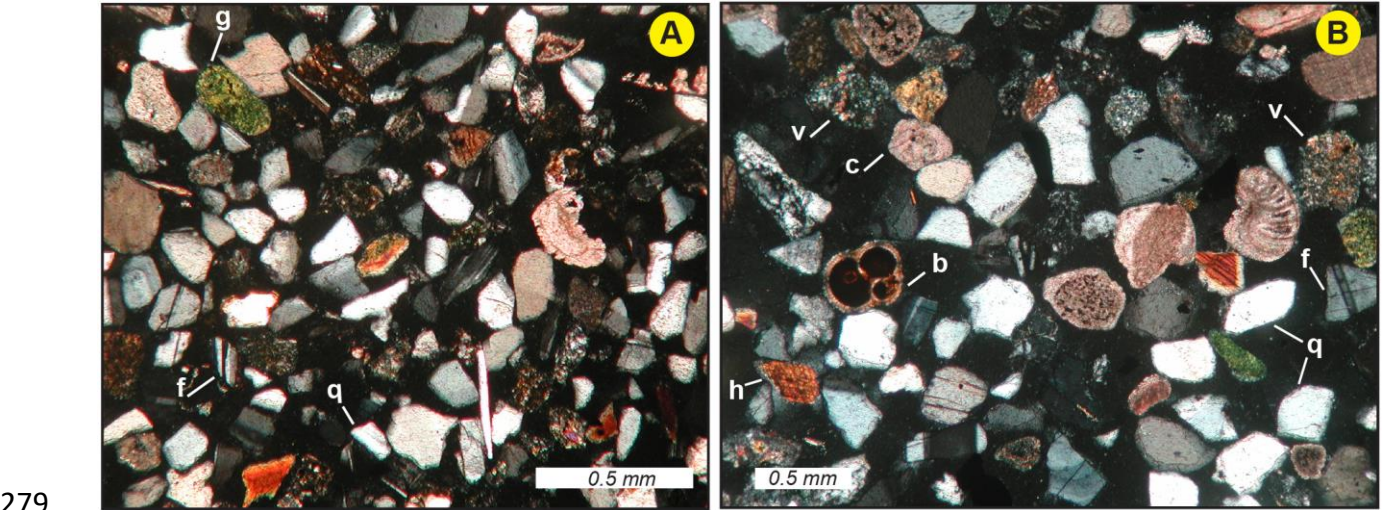
4.4 Composition of sands

The results from the modal analyses are reported in Table 2 and in the ternary diagrams of Fig. 6. The petrography under the optical microscope is shown in Fig. 7.



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

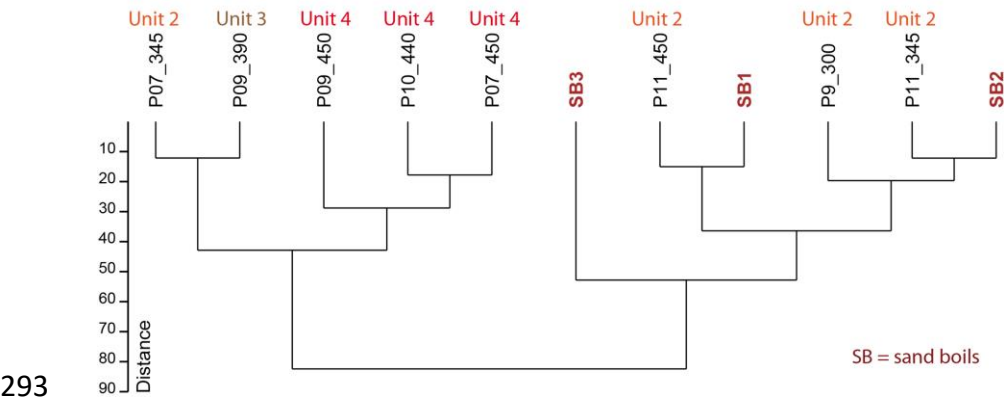
265 In general, sands from the cores are made up of quartz (single crystal and polycrystalline) ranging
 266 from 28.0 to 37.3% of the bulk rock. Total feldspars range from 20 to 33% and consist largely of
 267 plagioclase and subordinately K-feldspar (orthoclase and microcline). Both quartz and feldspar
 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 **Fig. 7** Photomicrographs of the examined sands. A) sand blow (sample SB1) and B) core sample
 280 (P09_450), showing the main components, q: quartz, f: feldspars, b: bioclasts, c. calcite spar, v.
 281 volcanics, h. hornblende, g. glauconite. Transmitted light, crossed polars.
 282
 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).
 292



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
	Micrite	1,3	1,0	3,3	1,3	2,3	1,0	2,0	1,0	1,0	0,3	0,7
C	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 (anfibol)	4,3	3,0	3,0	4,3	5,0	1,3	2,3	3,0	4,3	1,7	1,0
	Glaucinite	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 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).

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

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

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

6. Conclusions

- The study of the sands ejected at Rio Briceño valley (Ecuador) during the Mw 7.8 earthquake of April 2016 and the comparison with buried alluvial-marine Quaternary sediments, provided us with clues about the source layers identification.
- The composition and fabric characteristics, such as grain-size distribution, indicate that liquefaction processes affected mainly sand layers at depth of 2-4.5 m, and a relatively shallow source for the blowouts. The deeper coarser marine sands, characterized by higher amounts of carbonate grains, mainly bioclasts, were not affected by liquefaction.
- This study seems to corroborate previous findings that earthquake-induced liquefaction phenomena are not restricted to clean sands and well-sorted deposits, but may affect sand layers with significant amount of non-plastic silt.

Acknowledgement

A special thanks to “Geopier Foundation Company” (Davidson, North Carolina, USA) for financing the extensive geotechnical and geophysical investigations at Briceño bridge embankment,

372 to “Geoestudios” (Guayaquil, Ecuador) for gently assisting the proper performance of the site
373 campaign, and to Prof. Kervin Chunga (Universidad Estatal Península de Santa Elena, Ecuador) for
374 kindly sharing cartographies and scientific information of the studied area. Sedimentological
375 analysis are carried out within the project FAR2018 Unimore, Fontana.

376

377

378

379 REFERENCES

380

381 Alvarez, J. O., Schechter, D. S. (2017). Improving oil recovery in the Wolfcamp unconventional
382 liquid reservoir using surfactants in completion fluids. *Journal of Petroleum Science and*
383 *Engineering*, 157, 806-815.

384 Amoroso, S., Rollins, K.M., Wissmann, K., Minarelli, L. (2019). Estimation of lateral spreading by
385 SPT, CPTU and DMT following the 2016 Mw7.8 Ecuador earthquake. Conference paper at 6th
386 International Conference on Geotechnical and Geophysical Site Characterization. 7-11
387 September, 2020.

388 Amoroso, S., Rollins, K.M., Wissmann, K., Minarelli, L. (2020a). Estimation of lateral spreading
389 by SPT, CPTU and DMT following the 2016 Mw7.8 Ecuador earthquake. *Proceedings of the 6th*
390 *International Conference on Geotechnical and Geophysical Site Characterization - ISC'6*
391 *Conference*, 7-11 September 2020, Budapest, Hungary.

392 Amoroso, S., Rollins, K.M., Andersen, P., Gottardi, G., Tonni, L., García Martínez, M.F.,
393 Wissmann, K., Minarelli, L., Comina, C., Fontana, D., De Martini, P.M., Monaco, P., Pesci, A.,
394 Sapia, V., Vassallo, M., Anzidei, M., Carpena, A., Cinti, F., Civico, R., Coco, I., Conforti, D.,
395 Doumaz, F., Giannattasio, F., Di Giulio, G., Foti, S., Loddo, F., Lugli, S., Manuel, M.R.,
396 Marchetti, D., Mariotti, M., Materni, V., Metcalfe, B., Milana, G., Pantosti, D., Pesce, A.,
397 Salocchi, A.C., Smedile, A., Stefani, M., Tarabusi, G., Teza, G. (2020b). Blast-induced
398 liquefaction in silty sands for full-scale testing of ground improvement methods: insights from a
399 multidisciplinary study. *Engineering Geology*, 265, 17 pp,
400 <https://doi.org/10.1016/j.enggeo.2019.105437>

401 Arribas, J., and Tortosa, A. (2003), Detrital modes in sedimenticlastic sands from first- order
402 streams of the Iberian Range, Spain: the potential for sand generation of different sedimentary
403 rocks: *Sedimentary Geology*, 159, p. 275–303.

404 Ashmawy, A., Sukumaran, B., Hoang, V. (2003). Evaluating the Influence of Particle Shape on
 405 Liquefaction Behavior Using Discrete Element Modeling. Proc. Offshore and Polar Engineering
 406 Conference.

407 ASTM D2487-11 (2011). Standard Practice for Classification of Soils for Engineering Purposes
 408 (Unified Soil Classification System).

409 Beauval, C., Marinière, J., Laurendeau, A., Singaicho, J.C., Viracucha, C., Vallée, M., Maufroy, E.,
 410 Mercerat, D., Yepes, H., Ruiz, M., Alvarado, A. (2017). Comparison of observed ground motion
 411 attenuation for the 16 April 2016 Mw 7.8 Ecuador megathrust earthquake and its two largest
 412 aftershocks with existing ground motion prediction equations, *Seismol. Res. Lett.* 88(2A), pp.
 413 287–299.

414 Cantalamessa, G., Di Celma, C., Bianucci, G., Carnevale, G., Coltorti, M., Delfino, M., G. Ficarelli,
 415 M. Moreno Espinosa, D. Naldini, P. Pieruccini, L. Ragaini, L. Rook, M. Rossi, G. Tito, D. Torre,
 416 G. Valleri, W. Lanini (2001). A new vertebrate fossiliferous site from the Late Quaternary at San
 417 José on the north coast of Ecuador: preliminary note. *Journal of South American Earth Sciences*,
 418 14(3), 331-334.

419 Cantalamessa, G., Di Celma, C. (2004). Origin and chronology of Pleistocene marine terraces of
 420 Isla de la Plata and of flat, gently dipping surfaces of the southern coast of Cabo San Lorenzo
 421 (Manabí, Ecuador). *Journal of South American Earth Sciences*, 16(8), 633-648.

422 Chunga, K., Livio, F., Mulas, M., Ochoa-Cornejo, F., Besenon, D., Ferrario, M.F., Michetti, A.M.
 423 (2018). Earthquake ground effects and intensity of the 16 April 2016 Mw 7.8 Pedernales,
 424 Ecuador, earthquake: implications for the source characterization of large subduction
 425 earthquakes. *Bulletin of the Seismological Society of America*, 108(6), pp. 3384-3397.

426 Di Celma, C., Ragaini, L., Cantalamessa, G., Curzio, P. (2002). Shell concentrations as tools in
 427 characterizing sedimentary dynamics at sequence-bounding unconformities: examples from the
 428 lower unit of the Canoa Formation (Late Pliocene, Ecuador). *Geobios*, 35, 72-85.

429 Ego, F., Sébrier, M., Lavenue, A., Yepes, H., Egues, A. (1996). Quaternary state of stress in the
 430 Northern Andes and the restraining bend model for the Ecuadorian Andes. *Tectonophysics*,
 431 259(1-3), 101-116.

432 Fontana, D., Lugli, S., Dori, S. M., Caputo, R., Stefani, M. (2015). Sedimentology and composition
 433 of sands injected during the seismic crisis of May 2012 (Emilia, Italy): clues for source layer
 434 identification and liquefaction regime. *Sedimentary Geology*, 325, 158-167.

435 Fontana, D., Amoroso, S., Minarelli, L., Stefani, M. (2019). Sand Liquefaction Induced By a Blast
 436 Test: New Insights On Source Layer and Grain-Size Segregation Mechanisms (Late Quaternary,
 437 Emilia, Italy). *Journal of Sedimentary Research*, 89(1), 13-27.

438 Geotechnical Extreme Events Reconnaissance Association–Applied Technology Council (GEER-
 439 ATC). 2016 “Earthquake Reconnaissance, Mw 7.8, April 16th, 2016, Muisne, Ecuador”,
 440 Nikolaou, S., X. Vera-Grunauer, and R. Gilsanz (Editors), Version 1b, 604 pp., 2016. doi:
 441 10.18118/G6F30N.

442 Giona Bucci, M., Villamor, P., Almond, P., Tuttle, M., Stringer, M., Ries, W., Smith, C., Hodge,
 443 M., Watson, M. (2018). Associations between sediment architecture and liquefaction
 444 susceptibility in fluvial settings: the 2010–2011 Canterbury Earthquake Sequence, New Zealand.
 445 Eng. Geol. 237, 181–197.

446 Gutscher, M. A., Malavieille, J., Lallemand, S., Collot, J. Y. (1999). Tectonic segmentation of the
 447 North Andean margin: impact of the Carnegie Ridge collision. Earth and Planetary Science
 448 Letters, 168(3-4), 255-270.

449 Hammer, Ø., Harper, D.A.T., Ryan, P.D. (2001). PAST: Paleontological statistics software package
 450 for education and data analysis. Palaeontologia Electronica 4(1): 9pp. [http://palaeo-](http://palaeo-electronica.org/2001_1/past/issue1_01.htm)
 451 [electronica.org/2001_1/past/issue1_01.htm](http://palaeo-electronica.org/2001_1/past/issue1_01.htm)

452 Jaillard, E., Ordoñez, M., Benitez, S., Berrones, G., Jiménez, N., Montenegro, G., Zambrano, I.
 453 (1995). Basin development in an accretionary, oceanic-floored fore-arc setting: southern coastal
 454 Ecuador during late Cretaceous-late Eocene time.

455 Jaillard, E., Benitez, S., Mascle, G. H. (1997). Les déformations paléogènes de la zone d’avant-arc
 456 sud-équatorienne en relation avec l’évolution géodynamique. Bulletin de la Société géologique de
 457 France, 168(4), 403-412.

458 Kellogg, J. N., Vega, V., Stallings, T. C., Aiken, C. L. (1995). Tectonic development of Panama,
 459 Costa Rica, and the Colombian Andes: constraints from global positioning system geodetic
 460 studies and gravity. Special papers Geological Society of America, 75-75.

461 Lugli, S., Marchetti Dori, S., Fontana, D., (2007). Alluvial sand composition as a tool to unravel the
 462 Late Quaternary sedimentation of the Modena Plain, northern Italy. In: Arribas, J., Critelli, S.,
 463 Johnsson, M.J. (Eds.), Sedimentary Provenance and Petrogenesis: Perspectives from Petrography
 464 and Geochemistry. Geological Society of America Special Paper 420, pp. 57–72.

465 Maurer B.W., Green R.A., Wotherspoon L.M., Bastin S. (2019) The Stratigraphy of Compound
 466 Sand Blows at Sites of Recurrent Liquefaction: Implications for Paleoseismicity Studies.
 467 Earthquake Spectra: August 2019, 35(3), 1421-1440. <https://doi.org/10.1193/041818EQS097M>

468 Pedoja, K., Ortlieb, L., Dumont, J. F., Lamothe, M., Ghaleb, B., Auclair, M., Labrousse, B. (2006).
 469 Quaternary coastal uplift along the Talara Arc (Ecuador, Northern Peru) from new marine
 470 terrace data. Marine Geology, 228(1-4), 73-91.

471 Pedoja, K., Dumont, J. F., Lamothe, M., Ortlieb, L., Collot, J. Y., Ghaleb, B., Ghaleb, M. Auclair,
 472 V. Alvarez, Labrousse, B. (2006). Plio-Quaternary uplift of the Manta Peninsula and La Plata
 473 Island and the subduction of the Carnegie Ridge, central coast of Ecuador. *Journal of South*
 474 *American Earth Sciences*, 22(1-2), 1-21.

475 Reynaud, C., Jaillard, É., Lapierre, H., Mamberti, M., Mascle, G. H. (1999). Oceanic plateau and
 476 island arcs of southwestern Ecuador: their place in the geodynamic evolution of northwestern
 477 South America. *Tectonophysics*, 307(3-4), 235-254.

478 Sheppard, G., (1930). The geology of South Western Ecuador. *American Association of Petroleum*
 479 *Geologists Bulletin* 14, 263–309.

480 Smith, M.E., Wissmann, K. (2018). Ground improvement reinforcement mechanisms determined
 481 for the Mw 7.8 Muisne, Ecuador, earthquake. In: 5th Geotechnical Earthquake Engineering and
 482 Soil Dynamics Conference: Liquefaction Triggering, Consequences, and Mitigation - GEESDV
 483 2018, Austin, Texas, June 10-13, 2018, GSP 290, pp. 286-294.

484 Trenkamp, R., Kellogg, J. N., Freymueller, J. T., Mora, H. P. (2002). Wide plate margin
 485 deformation, southern Central America and northwestern South America, CASA GPS
 486 observations. *Journal of South American Earth Sciences*, 15(2), 157-171.

487 Vera-Grunauer, X.F., Lopez-Zhinda, S., Ordonez-Rendon, J., Chavez-Abril, M.A. (2019).
 488 Liquefaction case histories after the 2016 megathrust Pedernales earthquake in Ecuador. In: 7th
 489 International Conference on Earthquake Geotechnical Engineering – 7 ICEGE, Rome, Italy, June,
 490 17-20, 2019, pp. 805-820.

491 Wentz, F.J., van Ballegooy, S., Rollins, K.M., Ashford, S.A., Olsen, M.J. (2015). Large Scale
 492 Testing of Shallow Ground Improvements using Blast-Induced Liquefaction”, In: 6th
 493 International Conference on Earthquake Geotechnical Engineering – 6 ICEGE, Christchurch,
 494 New Zealand, Nov., 2-4, 2015.

495 Wissmann, K.J., van Ballegooy, S., Metcalfe, B.C., Dismuke, J.N., Anderson, C.K. (2015).
 496 Rammed aggregate pier ground improvement as liquefaction method in sandy and silty soils”,
 497 In: 6th International Conference on Earthquake Geotechnical Engineering - 6ICEGE,
 498 Christchurch, New Zealand, Nov., 2-4.

499 Ye, L., Kanamori, H., Avouac, J.P., Li, L., Cheung, K.F., Lay, T. (2016). The 16 April 2016, Mw
 500 7.8 (Ms 7.5) Ecuador earthquake: a quasirepeat of the 1942 Ms 7.5 earthquake and partial re-
 501 rapture of the 1906 Ms 8.6 Colombia–Ecuador earthquake. *Earth Planet. Sci. Lett.* 454, pp. 248–
 502 258, 2016

503 Zuffa, G.G., (1985). Optical analyses of arenites: influence of methodology on compositional
504 results. In: Zuffa, G. (Ed.), Provenance of Arenites NATO ASI 148.
505 Dordrecht/Boston/Lancaster, D. Reidel Publishing Company, pp. 165–189.

506