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1 **Late Quaternary sequence stratigraphy as a tool for groundwater exploration: lessons**
2 **from the Po River Basin (northern Italy)**

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13 University of Bologna.

14
15 **ABSTRACT**

16 Sequence stratigraphy, typically used for hydrocarbon exploration in ancient strata, can be
17 applied to late Quaternary successions to decipher complex spatial relations among their aquifers.
18 Late Pleistocene-Holocene strata of the Po Basin were investigated using a sequence-stratigraphic
19 approach to produce a high-resolution model useful for guiding groundwater exploitation. Since
20 facies tend to be diachronous across depositional basins, facies analysis was done within the
21 conformable intervals of strata revealed by sequence stratigraphy to accurately interpret and map
22 coeval lateral facies relations.

23 Volumetric assessments, sand-distribution mapping, hydraulic characterization of facies, and
24 spatial variations of hydraulic parameters revealed two aquifer systems (LST, HST) vertically
25 separated by an aquitard (TST). The LST aquifer consists of amalgamated fluvial sands (average
26 transmissivity: 3.5E-3 m²/s [37.7E-3 ft²/s]) with considerable width (> 25 km [> 16 mi]) preferentially

27 elongated downstream. The widespread TST permeability barrier is dominated volumetrically (~57%)
28 by very low-permeability estuarine deposits. The HST aquifer (average transmissivity: $5.4E-5$ m²/s
29 [$58.1E-5$ ft²/s]) is 5-10 km (~ 3-6 mi) wide, elongated parallel to the modern shoreline and
30 perpendicular to the LST aquifer.

31 Sequence-stratigraphic analysis at the parasequence scale revealed an almost unprecedented
32 level of detailed insight into aquifer/aquiclude dimensions and the complex distribution of hydraulic
33 parameters in the subsurface, showing that similar facies have different permeability values
34 depending on systems tract. In contrast, lithostratigraphic mapping obscures subsurface connectivity,
35 directional trends, and has minimal predictive power away from control. These insights should be
36 useful for guiding correlation and mapping of the deep subsurface and for hydrocarbon reservoir
37 modelers.

38

39 **INTRODUCTION**

40 Water is one of the most precious natural resources because it is essential to life, agriculture,
41 and industrial activities. In the last decades, expanding populations, rapid urbanization, pollution of
42 lakes and rivers, and climate change have increasingly affected water resources; water availability is
43 already an issue in many regions of the world (Vörösmarty et al., 2000; Morrison et al, 2009). There
44 is thus a growing need for water protection and management, especially in terms of flow rates and
45 quality. Fresh groundwater is definitely a critical resource (Maliva, 2016), and an improvement of
46 the methods and techniques used in groundwater exploration and aquifer exploitation may be crucial
47 for future scenarios. In addition, insights gained from studying shallow aquifers, where abundant and
48 closely spaced data are commonly available, can be readily applied to deeper fluid-flow systems, such
49 as hydrocarbon reservoirs.

50 Although most commonly used for hydrocarbon exploration, sequence-stratigraphic concepts
51 (Mitchum et al., 1977; Vail et al., 1977a, b; Van Wagoner et al., 1988, 1990; Galloway, 1989;
52 Posamentier et al., 1992) have also been adopted in groundwater investigations (e.g., Ehman and

53 Edwards 2014) for detailed hydrostratigraphic characterization (Galloway and Sharp, 1998). Several
54 studies have used sequence-stratigraphic analysis to produce geological models and evaluate the
55 distribution and connectivity of major regional aquifer systems (Weissman and Fogg, 1999; Houston,
56 2004; Ponti et al., 2007; Edwards, 2009; Edwards et al., 2009a, b; Scharling et al., 2009; Velasco et
57 al., 2012; Chamberlain et al., 2013; Ehman and Edwards, 2014). However, the true potential of
58 sequence stratigraphy for predicting relations between lithofacies and hydrofacies has yet to be
59 realized (Maliva, 2016).

60 In this study, we applied the sequence-stratigraphic approach at high resolution to investigate
61 alluvial (Late Pleistocene) and coastal-shallow marine (Holocene) deposits of the Po Plain, with a
62 specific focus on characterizing them as groundwater systems.

63 The study area (~1,900 km² [730 mi²]) is located south of the modern Po River, between the
64 city of Ferrara and the Adriatic Sea (Figure 1). The abundance of closely-spaced geological tests
65 (Figure 1) and a well-established chronostratigraphic framework from previous studies (i.e., Amorosi
66 et al., 2017a, b; Bruno et al., 2017; Campo et al., 2017) make this sector an appealing site to develop
67 a hydrostratigraphic approach.

68 The Po Plain (northern Italy) is one of the widest and most populated alluvial plains in Europe,
69 with remarkable economical activities. Basin-wide groundwater investigations have been conducted
70 by Regione Emilia-Romagna and ENI-Agip (1998), and Regione Lombardia and Eni-Divisione Agip
71 (2002), in order to map potential aquifer systems and evaluate their volumes and petrophysical
72 characteristics. South of the Po River (Figure 1), Regione Emilia-Romagna and ENI-Agip (1998)
73 applied a pioneering sequence-stratigraphic approach that outlined aquifer distribution within the
74 Pliocene to Quaternary succession. The basin fill was subdivided into third-order depositional
75 sequences (*sensu* Mitchum et al., 1977), following the identification on seismic profiles of major
76 unconformities of tectonic origin. Eight fourth-order, transgressive-regressive successions controlled
77 by interglacial-glacial fluctuations (Amorosi et al., 2008) were traced within the youngest

78 depositional sequence of the Po Basin. Each fourth-order succession corresponds to an aquifer
79 complex (Regione Emilia-Romagna and ENI-Agip, 1998).

80 On a regional scale, Amorosi and Pavesi (2010) built a generalized model of spatial distribution
81 of aquifer systems from the Apennines margin to the Adriatic Sea coast. According to this model,
82 hydrostratigraphic units are bounded by transgressive surfaces, which lie a few meters below the base
83 of highstand marine sands (i.e., “coastal aquifers”) and roughly correspond to the top of amalgamated,
84 lowstand fluvial gravel and sand bodies (i.e., “alluvial aquifers”).

85 North of the Po River, several studies integrating stratigraphic, geomorphological and
86 geophysical information have documented the aquifer architecture of Quaternary strata, and
87 developed flow models incorporating sedimentary heterogeneity (Bersezio et al., 1999, 2004, 2007;
88 Felletti et al., 2006; Zappa et al., 2006; Mele et al., 2012, 2013, 2015). South of the Po River, in the
89 Ferrara region, which corresponds approximately to the study area in this paper (Figure 1), Molinari
90 et al. (2007) mapped aquifer systems of Quaternary age. Bonzi et al. (2010) mapped the gross-
91 thickness of the phreatic aquifer along the Emilia-Romagna coast, mainly based on lithostratigraphic
92 correlations. Local hydrogeological studies from the same area focused mostly on the quantification
93 of surface water–groundwater interactions (Mastrocicco et al., 2014), groundwater dynamics,
94 salinization processes in coastal aquifers (Antonellini et al., 2008; Mastrocicco et al., 2012;
95 Giambastiani et al., 2013, 2017), and aquifer recharge and their vulnerability (Filippini et al., 2015,
96 2016).

97 The aims of this study are: (i) to show the role of detailed stratigraphic study and facies analysis
98 for aquifer characterization in the Po Basin and (ii) to test the potential of a sequence-stratigraphic
99 approach to support construction of a robust hydrostratigraphic model of Quaternary aquifers that
100 integrates regional and local scales.

101 Heterogeneity (i.e., spatial variation of hydraulic properties) represents one of the most
102 challenging variables in aquifer (and hydrocarbon reservoir) characterization, and its origin is mostly
103 inherent to the depositional history of the strata of interest (Maliva, 2016). The hydraulic conductivity

104 of siliciclastic deposits largely depends on grain size, sorting and matrix content, which in turn are a
105 function of the source area (i.e., mineralogic composition), transport processes, and hydrodynamic
106 conditions within the depositional environment. Interpretation of depositional processes and
107 environmental settings is difficult if stratigraphic subdivisions are based only on basic lithologic
108 descriptions (conventional lithostratigraphic approach), especially when the dataset is largely
109 composed by cores. On the other hand, the analysis of vertical facies relations (following Walther's
110 law, 1894) and the identification of facies associations (Collinson, 1969; Reading, 2009) allows
111 reliable environmental reconstructions that can be useful for predicting spatial variations of hydraulic
112 conductivity (and its related parameters) from limited site-specific information.

113 Therefore, we adopted a detailed sequence-stratigraphic approach using key stratigraphic
114 surfaces (i.e., sequence boundary, transgressive surface, and maximum flooding surface) as a guide
115 to stratigraphic correlation, and considered facies associations as fundamental architectural units
116 because they can be mapped and used for building groundwater models (Phillips et al. 1989; Davis
117 et al. 1993; Hornung and Aigner 1999). The classification of siliciclastic sediments, however, is based
118 primarily on grain size and grain sorting (i.e., lithology), and heterogeneity in siliciclastic aquifers is
119 mainly controlled by depositional textural variations and fabric/bedding (e.g., Maliva, 2016). For this
120 reason, in order to make stratigraphic analysis tightly linked to groundwater hydrology, we firstly
121 distinguished four main lithofacies: two "classic", net-to-gross end-members, corresponding to sand
122 and clay, respectively; and two intermediate grain-size classes (muddy sand and sandy mud). Thus,
123 for each systems tract (lowstand, LST; transgressive, TST; highstand, HST), we made quantitative
124 estimates of volumes and net-thickness of all lithofacies and facies assemblages (i.e., combination of
125 lithology, sedimentary structures/bedding, body fossils and accessory materials). For the most
126 "prospective" lithofacies in terms of groundwater storage (i.e., sand), we mapped and quantified the
127 spatial distribution and net-thickness of major sediment bodies (i.e., potential aquifers) within each
128 systems tract.

129 This study provides a path for making the hydrostratigraphic framework an operational tool for
130 future 3-D aquifer modeling, with the integration of hydraulic parameters (i.e., hydraulic
131 conductivity, “K”, and transmissivity, “T”), specifically calculated for each facies association and
132 potential aquifer within LST, TST and HST.

133

134 **GEOLOGICAL SETTING**

135 The Po Plain represents the surface expression of a rapidly subsiding foreland basin (ca. 1 mm/y
136 [0.04 in/y]; Amorosi et al., 2016) bounded by the Alps in the north and by the Apennines to the south
137 (Figures 1, 2). The Po River, the longest river in the Italian peninsula (652 km [405 mi]), flows into
138 the Adriatic Sea crossing the entire plain, from west to east (Figures 1, 2). This trunk river acts as a
139 major conveyor belt for the sediment delivered by its Apenninic and Alpine tributaries.

140 The subsurface of the Po Basin has been investigated extensively in the last decades for both
141 hydrocarbon and water exploration, and the overall basin stratigraphy has been reconstructed at a
142 large scale based on seismic surveys and well-log interpretations (AGIP Mineraria, 1959; Pieri and
143 Groppi, 1981; Dondi and D’Andrea, 1986; Dalla et al., 1992; Ori, 1993; Regione Emilia-Romagna
144 and ENI-AGIP, 1998; Regione Lombardia and ENI Divisione AGIP, 2002; Scardia et al., 2006, 2012;
145 Ghielmi et al., 2010, 2013; Garzanti et al., 2012; Rossi et al., 2015). South of the Po River, the
146 Pliocene-Quaternary basin fill was subdivided into six third-order depositional sequences (*sensu*
147 Mitchum et al., 1977) about 100-1000 m (~ 330-3300 ft) thick, mapped as unconformity-bounded
148 stratigraphic units (UBSU) by Regione Emilia-Romagna and ENI-AGIP (1998; Figure 2A). Tectonic
149 uplift and subsidence exerted a major control on the origin and development of sequence-bounding
150 unconformities. Magnetostratigraphic studies (Muttoni et al. 2003) estimated an age of about 0.87
151 Ma for the lower boundary (i.e, surface F, Figure 2A) of the uppermost USBU (Po Supersynthem of
152 Amorosi et al., 2008). The identification of a “higher order” stratigraphic unconformity (i.e., surface
153 G; Figure 2A) allowed further subdivision of the Po Supersynthem into Lower and Upper Po
154 Synthems (Amorosi and Pavesi, 2010).

155 Eight fourth-order transgressive-regressive (T-R) successions have been recognized within the
156 Po Supersynthem (Amorosi et al., 2008). Beneath the modern coastal plain, these units record the
157 cyclic alternation of vertically-stacked marine and continental deposits (Amorosi et al., 2004). Based
158 on pollen profiles, radiocarbon dates, and electron-spin-resonance dating, the sedimentary cyclic
159 architecture of T-R successions has been linked to glacio-eustatic fluctuations in the Milankovitch
160 (100 ky) band (Amorosi et al., 2004, 2008; Antonioli et al., 2009). In coastal areas, individual T-R
161 successions are up to 100 m (~330 ft) thick and consist of basal transgressive-regressive coastal
162 wedges (Figure 2B), overlain by thick alluvial strata (Figure 2B). In more landward positions, close
163 to the Apenninic margin and beneath the modern Po River, the T-R successions are entirely made up
164 entirely of continental deposits, with an upward increase of the sand/mud ratio and fluvial-channel
165 clustering (Amorosi et al., 2008; Campo et al., 2016).

166 This stratigraphic architecture has important implications from a groundwater-exploration
167 perspective. Five T-R successions (1 to 5) were identified within the Upper Po Synthem (Amorosi et
168 al., 2008), the youngest of which (Holocene T-R 5), is incomplete (Figure 2B). Within each
169 succession, the basal, fine-grained deposits represent aquitards or aquicludes (i.e., major permeability
170 barriers), whereas amalgamated alluvial-fan gravels and sandy fluvial channel-belts form the main
171 aquifer systems (A4 to A1, Figure 2B). These aquifers are typically confined, because they are
172 sandwiched between thick and laterally continuous permeability barriers. Holocene sand bodies form
173 an unconfined aquifer, termed A0 (Molinari et al., 2007). At proximal locations, A0 consists of
174 isolated fluvial-channel sands, whereas downstream it comprises mostly coastal sands (Figure 2B).

175 Despite the use of a non-uniform terminology and different scales and methods of investigation,
176 previous studies had the merit of identifying aquifer groups at the scale of the entire Po Basin.
177 However, by choosing the abrupt lithological changes from laterally extensive and amalgamated
178 fluvial-channel bodies to overlain muddy units as key surfaces for stratigraphic subdivisions, they did
179 not account for the importance of discontinuities in basin-fill architecture and obscured genetic
180 relations of strata. A “classic” sequence stratigraphic approach, and in particular, the recognition and

181 mapping of sequence boundaries (red lines, Figure 2B), enables a clear recognition and
182 compartmentalization of coarse-grained sedimentary bodies (aquifers) within mud-prone intervals
183 (aquitards), allowing the identification of depositional sequences and more reliable predictions of the
184 spatial distribution of aquifers.

185 Furthermore, limited attention was generally paid to the aquifer heterogeneity issue by both
186 the regional surveys and local studies. These latter have mostly been conducted for hydrogeological
187 purposes and did not sufficiently take into account facies relations, and their implications in terms of
188 hydraulic characterization and geometries of aquifers and aquitards.

189

190 **METHODS**

191 **Database**

192 This work relies upon the Regione Emilia-Romagna (RER) stratigraphic database, and on
193 additional fifteen continuously cored boreholes (cores EM, Figure 1). Cores EM were recovered
194 between 2014 and 2016 as part of a collaborative project between the University of Bologna and
195 ExxonMobil Upstream Research Company, Houston, Texas (Amorosi et al., 2017a, b; Bruno et al.,
196 2017).

197 The dataset incorporates 656 sedimentological, hydrogeological, and geotechnical reports (see
198 Figure 1, for their spatial distribution), mostly acquired by RER as part of the geological mapping
199 project of Italy at 1:50,000 scale. Reports generally include the following information: test location;
200 basic lithologic descriptions (facies interpretation is given in very few cases), core pictures,
201 permeability test results, geotechnical measurements, and graphs of laboratory tests. The RER
202 Geological Survey guarantees free access to its database through a webGis application available only
203 in Italian at the following link: <http://ambiente.regione.emilia-romagna.it/geologia/cartografia/webgis-banchedati>.

205 In the study area (Figure 1), the average test spacing is 0.5-1 km (0.3-0.6 mi). More specifically,
206 we used 102 core descriptions (average depth 45 m [147 ft]), including information about grain size,

207 color, pedogenic features, accessory materials (e.g., roots, peats, vegetal fragments, bioturbation,
208 carbonate nodules), pocket penetration values and, in a few cases, radiocarbon dates and permeability
209 tests.

210 In order to identify the base and top of potential aquifers, nine water-well reports (average depth
211 60 m [197 ft]) were considered: in spite of their general poor quality, these data provide sufficient
212 lithologic (clay vs. sand) information.

213 A total of 530 cone penetration tests with piezocone (CPTU) profiles were utilized to improve
214 lithofacies identification and stratigraphic correlation (Amorosi and Marchi 1999; Styllas, 2014;
215 Amorosi et al., 2015; Misseaen et al., 2015). In fourteen cases (i.e., EM cores 1, 2, 3, 5, 7, 8, 9, 10,
216 11, 12, 13, 14, 16, and 17), CPTU profiles were calibrated in detail to continuous core data (Figure
217 3).

218

219 **Lithofacies identification and characterization**

220 Lithofacies characterization was performed following an empirical method based on qualitative
221 grain-size analysis on fresh cores (i.e., field description), supported by 1:1 core to CPTU lithologic
222 comparison (Figure 3A, B). Sleeve friction (f_s) and cone resistance (Q_c) values were used to calculate
223 the friction ratio ($FR = f_s/Q_c * 100$), which represents a major tool for soil-texture classification
224 (Begemann, 1965; Schmertmann, 1969; Robertson, 2010). Additional techniques for lithologic
225 interpretation based on cone penetration tests (Robertson, 1986, 1989, 2010; Maliva, 2016) were also
226 considered.

227 Four distinctive lithofacies (see Figure 3C) were identified and classified as follows:

228 - Sand (S): from coarse to very-fine sand. Resistance to penetration at the tip of the penetrometer
229 (Q_c) is > 5 MPa, with an associated negative pore pressure (U) (Figure 3B). Friction ratio is $< 1\%$
230 (Figure 3B);

231 - muddy Sand (mS). Cone resistance measurements fall in the range of 2-5 Mpa, with low-to-
232 negative pore pressure values. Friction ratio is 0.6-1.2% (Figure 3B);

233 - sandy Mud (sM). Cone resistance is < 2 MPa. The pore pressure curve may show characteristic
234 see-saw profiles in the range of low-to-high positive values. The friction ratio curve is also irregular,
235 with percentages between 0.8% and 3% (Figure 3B);

236 - Mud (M): from silt to clay. Typical cone resistance profiles range between 0.1 and 2 MPa,
237 with positive pore pressure values. Paleosols exhibit $Q_c > 2$ MPa (Amorosi et al., 2017a). Friction
238 ratios range from 1% to 5%, in line with values typically used for silt and clay recognition from cone
239 penetration tests (i.e., Robertson and Campanella, 1983; Bakker, 2006; Figure 3B).

240 In order to improve our understanding of aquifer heterogeneity, we also considered facies
241 associations. Facies associations, which consist of two or more lithofacies (Figure 3C, D), are crucial
242 to predict the geometry of sedimentary bodies, their spatial distribution and lateral relations, with
243 intrinsic implications for the characterization of hydraulic properties trends. Lithofacies are not only
244 essential components of the lower-order facies associations, but also equally important as the first
245 basic subdivision between “high” vs “low” permeability units (which is mostly a function of grain-
246 size distribution). Lithofacies and facies associations thus were used to characterize different types
247 of information, at different scales.

248 The detailed description and interpretation of each individual sedimentary facies lies outside
249 the aim of this article. A comprehensive analysis of all facies associations listed in Table 1 is available
250 in Amorosi et al., (2017a, b), Bruno et al., (2017) and Campo et al. (2017). The reader is referred to
251 these studies for further details.

252

253 **Hydraulic parameters**

254 As for hydraulic parameters (i.e., horizontal hydraulic conductivity “K” and transmissivity
255 “T”), all values utilized in this study were obtained from *in-situ* borehole measurements from the
256 study area (see Figure 1 for location). These data were extrapolated from:

257 - permeability test reports (i.e., aquifer pumping tests from cores and water wells, and
258 dissipation tests from CPTUs) from the RER database;

259 - hydrogeological studies based on aquifer pumping tests (Gargini et al., 2003);
260 - hydraulic (Mazzini et al., 2006) and hydrostratigraphic studies (Regione Emilia-
261 Romagna and ENI, 1998; Molinari et al., 2007).

262 Since hydraulic conductivity of siliciclastic deposits mostly depends on their depositional
263 texture, which includes grain size, sorting, and matrix content, specific K ranges can reasonably be
264 considered diagnostic of distinct facies associations. Therefore, all available K values were matched
265 in detail against the local stratigraphy, before any sequence stratigraphic interpretation. This operation
266 led us to a basic, but reliable initial hydraulic characterization of facies associations and of their
267 lithologic components (i.e., lithofacies).

268 Figure 4 shows K the range of K values across the main facies associations of the Lower
269 Pleistocene-Holocene (LP-H) succession. For each facies association, K values may vary up to three
270 orders of magnitude (i.e., OFF/PRD facies association, Figure 4). Such wide ranges are a function of
271 many variables, such as the technique used for K measurement, the number of data points available,
272 the “stratigraphic position” (i.e., the depth of individual K measurements) which could be
273 significantly affected by sediment compaction, and intrinsic heterogeneities within sediment bodies.

274 A first analysis of K values displays three main clusters (i.e., very-low, low and moderate
275 hydraulic conductivity) that roughly correspond to the fine-grained, homogeneous, and coarse-
276 grained facies associations respectively (Figure 4). Excluding the non-significant overlap between
277 each cluster, K values of fine-grained facies are invariably lower than $3\text{E-}8$ m/s [$9.85\text{E-}8$ ft/s], i.e.
278 about one order of magnitude lower than in heterolithic facies (ca., $3\text{E-}7$, [$9.85\text{E-}7$ ft/s]), and at least
279 two orders lower than in sandy facies ($5.3\text{E-}6$, [$17.40\text{E-}6$ ft/s]; Figure 4). Therefore, mean values of
280 hydraulic conductivities can be considered sufficiently representative of facies associations at the
281 scale of our investigation to set up a preliminary and *conceptual* hydrostratigraphic model of the
282 entire LP-H succession.

283 Individual K values (Figure 4) were then framed into a systems tract (LST, TST and HST)
284 context to discern the relation of high- vs low- permeability hydrostratigraphic units to lateral facies
285 variations.

286 The average transmissivity (T) of high-permeability sediment bodies (i.e., aquifers) was
287 calculated according to the formula:

288 - $T=K*h$, where

289 'T' (m²/s) is transmissivity; 'K' (m/s) is the average horizontal hydraulic conductivity of facies
290 associations; and 'h' is the average net-thickness of the corresponding facies association within LST,
291 TST, and HST (see Table 1).

292 Since we are not modeling specific flow paths, we used an average transmissivity values
293 considering the average thickness of isopachous sandbodies, to provide a simple, but reliable
294 quantitative distinction between high- vs low-permeability lithosomes (i.e., potential
295 aquifers/aquitards). In order to set up a proper hydrological model, anisotropy (at different scales)
296 and thickness variations of individual sandbodies should be taken into account.

297

298 **Sequence-stratigraphic approach**

299 Facies tend to be diachronous across a depositional basin and facies boundaries commonly
300 transgress geologic time. Facies analysis must be done within conformable intervals of strata to
301 accurately interpret and map coeval lateral facies relations (e.g., Walther, 1894; Middleton, 1973;
302 Reading, 1978; Walker, 1984; Van Wagoner et al., 1990). Facies analysis and mapping that does not
303 account properly for surfaces of discontinuity is apt to lead to inaccurate to unrealistic interpretations
304 of rock-property distribution. Sequence stratigraphy is “the study of genetically related facies within
305 a framework of chronostratigraphically significant surfaces” (Van Wagoner et al., 1990). Each of
306 these surfaces is a distinct physical boundary that, over the extent of the surface, separates all of the
307 strata above from all of the strata below. Therefore, sequence-stratigraphic surfaces, which can be

308 correlated using well logs, cores, or outcrops, provide a high-resolution chronostratigraphic
309 framework for facies analysis.

310 Sequence-stratigraphic correlations reveal genetically related strata and thus enable accurate
311 prediction of rock properties using Walther's Law and process-based models. Such correlations,
312 however, commonly yield results that differ substantially from those obtained by conventional
313 lithostratigraphic correlations that rely on tops of sandstone or mudstone intervals (Van Wagoner et
314 al., 1990). In order to demonstrate the efficacy of a sequence stratigraphic approach to the analysis of
315 Quaternary deposits, we followed Van Wagoner, et al. (1990) and used our dataset to compare
316 lithostratigraphic vs sequence-stratigraphic correlation techniques (Figure 5).

317 For example, in a retrogradational parasequence set, such as the TST, lithostratigraphic
318 correlation leads to an interpretation of a single continuous sand body at the top of the unit that, in
319 fact, comprises intervals that are not connected, while exaggerating the discontinuities of underlying
320 porous intervals (e.g., Van Wagoner et al., 1990, their Figure 18 and our Figure 5). From core
321 descriptions (Bruno et al., 2017) we know that these sandstone units were deposited as a transgressive
322 barrier island; the lithostratigraphic correlation implies that the barrier island was about 20-km wide
323 (Figure 5B), which is an order of magnitude wider than any barrier island system observed today in
324 the area (Figures 5A and 6B, C).

325 The sequence-stratigraphic approach is particularly useful in subdividing the broader scale T-
326 R 'cycles' to build detailed maps. This approach explicitly recognizes a hierarchy of
327 flooding/transgressive surfaces of varying significance and extent. Within a single depositional
328 sequence, there are two major flooding/transgressive surfaces: one at the top of the lowstand systems
329 tract, and the other at the top of the transgressive systems tract (maximum-flooding surface). Between
330 these two major surfaces, there commonly are numerous other flooding/transgressive surfaces of
331 smaller extent that bound parasequences in the transgressive systems tract (Figure 5A). The potential
332 for confusing which surface is of what extent is significant and miscorrelation is common in regional

333 studies, especially if the data used to correlate are widely spaced. The sequence-stratigraphic
334 approach, by focusing attention on the stratal hierarchy helps avoid such errors.

335

336 **Chronological data and stratigraphic mapping**

337 The chronological framework relies upon 89 published radiocarbon dates (Amorosi et al.,
338 2017a, b; Bruno et al., 2017; Campo et al., 2017).

339 Stratigraphic data were georeferenced, converted in jpg format and uploaded into the software
340 Petrel (Schlumberger), which was used for:

- 341 - three-dimensional lithofacies and facies-association correlation through the construction
342 of a grid of cross-sections;
- 343 - sequence-stratigraphic analysis, i.e. identification and correlation of major stratigraphic
344 surfaces (SB, TS, and MFS);
- 345 - gross-thickness mapping of the LP-H Sequence and of its component systems tracts
346 (LST, TST, and HST);
- 347 - quantitative volumetric (km³) estimates of the LP-H Sequence, LST, TST, and HST
348 (Table 1) in areas defined by polygons, based on the stratigraphic position of bounding
349 surfaces;
- 350 - quantitative assessments of volumetric percentages and net-thickness of distinct
351 lithofacies and facies associations within the LP-H Sequence, and across systems tracts
352 (LST, TST, and HST; Tables 1, 2). All data-points available from the database (Figure
353 1) were analyzed. The construction of discrete templates (i.e., lithofacies, facies
354 associations etc..) led to the quantification, for each data-point, of the corresponding
355 percentage and net-thickness of lithofacies and facies associations within the selected
356 stratigraphic interval. In order to provide a more significant spatial distribution of the
357 data, given the average test spacing of 0.5-1 km (0.3-0.6 mi; see Figure 1), we
358 considered 1 data-point/square kilometer (0.4 square mile). On the basis of hundreds

359 of equally-spaced data measurements, we calculated the arithmetic mean in terms of
360 volumetric percentages (%) and net-thicknesses (m) of lithofacies and facies
361 associations within the LP-H Sequence and in each systems tract (Tables 1, 2);
362 - volumetric estimation (km³) of lithofacies and facies associations for the LP-H Sequence
363 and its component systems tracts (LST, TST and HST), on the basis of total sediment
364 volumes and volumetric percentages of lithofacies and facies associations, respectively
365 (Tables 1, 2).
366 - evaluation and mapping of sand distribution within each systems tract (i.e., LST, TST,
367 and HST). Identical procedures as those utilized for building gross net-thickness maps;
368 - sand net-thickness mapping of the LP-H Sequence, LP and H intervals, and systems
369 tracts (LST, TST, and HST).

370 For all maps, the best interpolation was achieved by using the convergent interpolation method
371 available in Petrel. A normal extrapolation type was set for the convergent gridding process. Grid and
372 size position was directly determined from the selected input data (e.g., points) and boundary (e.g.,
373 polygon of the study area), with a grid increment of 50 for x-y increments. However, all maps were
374 edited manually, to incorporate geological interpretation and regional trends.

375

376 **LATE PLEISTOCENE-HOLOCENE SEQUENCE STRATIGRAPHY**

377 Understanding of the stratigraphy of the Late Pleistocene-Holocene succession in the study area
378 (Figure 1) and adjacent regions has been considerably improved by several recent, multi-proxy
379 sequence-stratigraphic studies focused both on alluvial (Amorosi et al., 2017a; Campo et al., 2016)
380 and coastal (Amorosi et al., 2017b; Bruno et al., 2017; Campo et al., 2017) deposits.

381 Based on these high-resolution studies, we constructed a three-dimensional framework across
382 the study area. We include here three cross-sections to depict key aspects of the facies architecture
383 and sequence stratigraphy of the Late Pleistocene-Holocene Sequence (Figure 6). Transects A and B

384 run parallel to the present shoreline (Figure 1), across alluvial (Figure 6A) and coastal (Figure 6B)
385 deposits, respectively. A transverse profile is shown in Figure 6C.

386 Late Pleistocene and Holocene deposits exhibit strikingly contrasting lithologic features: the
387 Late Pleistocene (LP) succession consists of well-drained floodplain muds and amalgamated fluvial
388 sands, up to 30 m (~98 ft) thick (Figure 6A, B). Thick sand bodies are the dominant feature in the
389 northern sector (Figure 6C), beneath the modern Po River. These sands exhibit broad spatial
390 continuity (ca. 30 km [19 mi] in Figure 6A, B, and > 50 km [> 30 mi] in Figure 6C). The overlying
391 Holocene (H) succession consists mostly of soft, fine-grained deposits with distinctive downdip
392 facies changes from poorly-drained alluvial facies, through swamp (freshwater) and lagoonal
393 (brackish) clays, down to coastal and shallow-marine deposits (Figure 6). The lower part of the
394 Holocene coastal wedge is marked by the vertical transition from estuarine muddy facies to
395 transgressive barrier sands. These deposits are overlain by laterally extensive (> 35 km [> 21 mi])
396 shallow-marine and prodelta muds, up to 20 m (~65 ft) thick (Figure 6B, C). A broad lateral continuity
397 and uniform thickness (up to 15 m (~49 ft)) also characterize the sand sheet in the upper portion of the
398 coastal succession (Figure 6B, C).

399 From a sequence-stratigraphic perspective, the basal Sequence Boundary (SB) is represented
400 by the Inceptisol developed at the onset of Marine Isotope Stage (MIS) 2, about 30 ky BP (Amorosi
401 et al., 2017a; Campo et al., 2017), which is laterally correlative with the base of an extensive channel-
402 belt sand body fed by the Po River (Amorosi et al., 2016). The Lowstand Systems Tract strictly
403 coincides with Late Pleistocene deposits (Figure 6). The LST is characterized by an aggradational
404 stacking pattern of well-drained floodplain facies and amalgamated fluvial-channel sand bodies
405 deposited during the Last Glacial Maximum (Amorosi et al., 2017a; Campo et al., 2016, 2017).

406 The Transgressive Surface (TS) is interpreted at the widespread and abrupt facies change from
407 aggradational, well-drained LP floodplain deposits (LST) to retrogradational, poorly-drained and
408 organic-matter-rich estuarine sediments of Holocene age (Figure 6A, C); it corresponds to the
409 weakly-developed Inceptisol dated to ca. 12.6 ky BP (i.e., Younger Dryas paleosol of Amorosi et al.,

410 2017a). As a whole, the Transgressive Systems Tract (TST) shows a diagnostic deepening-upward,
411 retrogradational trend from basal, poorly-drained alluvial facies to shallow-marine deposits. At
412 proximal locations, the TST is poorly preserved. Small-sized fluvial bodies are locally associated
413 with the Younger Dryas paleosol (i.e., TS), as shown in Figure 6.

414 Within the Holocene strata, the Maximum Flooding Surface (MFS) highlights the transition
415 from a retrogradational to a progradational stacking pattern of facies associations and marks the
416 maximum landward migration of the shoreline. At seaward locations, the MFS lies within relatively
417 homogeneous shallow-marine muds, and therefore it is tracked mostly on the basis of paleontological
418 data (Amorosi et al., 2017b; Campo et al., 2017). Landwards, this surface lies within organic-matter-
419 and peat-rich deposits dated to about 7 ky BP (Amorosi et al., 2017b; Bruno et al., 2017). On the
420 interfluves, where TST is not preserved (Figure 6A), the MFS and TS essentially coincide. The HST
421 displays an overall shallowing-upward tendency: beneath the modern coastal plain, laterally extensive
422 prodelta muds are capped by a thick, prograding succession of delta-front and beach-ridge sands
423 (Figure 6B, C). Upstream, organic-matter-rich, transgressive estuarine deposits are progressively
424 replaced by poorly-drained delta-plain facies (Figure 6A, C). TST and HST form the Holocene
425 succession in the study area.

426

427 **QUANTITATIVE ASSESSMENT OF LITHOFACIES AND FACIES ASSOCIATIONS**

428 Lithofacies/depositional facies identification, along with sequence-stratigraphic interpretation
429 enabled volumetric and net-thickness estimates of facies associations and lithofacies within the LP-
430 H depositional sequence of the Po Basin. The subdivision of the Holocene interval into TST and HST
431 provides the basis for detailed quantitative assessments and mapping in an aquifer-characterization
432 perspective.

433 Average volumetric percentage (%), volume estimation (km³), and average net-thickness (m)
434 of main facies associations (Table 1) and lithofacies (Table 2) were calculated for the entire LP-H

435 depositional sequence and for each systems tract, along with total sediment volumes (Table 1). Gross-
436 thickness maps (Figure 7) were also built as a support to interpreting the quantitative data.

437 **Late Pleistocene-Holocene (LP-H) Depositional Sequence** – The gross-thickness map (Figure
438 7A) shows the largest values of about 50 m (~165 ft) in the NE sector of the study area, whereas the
439 lowest thickness is recorded in the SW (~16 m [52 ft]). The total volume of the LP-H Sequence is
440 65.7 km³ (15.8 mi³; Table 1). In terms of facies associations, volumetrically abundances (> 10% of
441 total volume) at the sequence-scale are: fluvial channel sands (23.7% or 15.6 km³ [3.7 mi³]), well-
442 drained floodplain muds (11.4% or 7.5 km³ [1.8 mi³]), swamp clays (22.2% or 14.6 km³ [3.5 mi³]),
443 and coastal (transgressive-barrier, delta-front, and beach-ridge) sands (10.9% or 7.1 km³ [1.7 mi³];
444 Table 1).

445 About 50% (~32.9 km³ [7.9 mi³]) of the entire depositional sequence consists of mud (Table 2).
446 Sand (39.2% or 25.1 km³ [6 mi³]) and muddy sand (9.5% or 6.2 km³ [1.5 mi³]), taken together, form
447 slightly less of the remaining 50%, whereas sandy mud accounts for just 2.3% (1.5 km³ [0.4 mi³]) of
448 the total volume. Mud and sand lithofacies show a comparable net-thickness of about 16 meters (~52
449 ft). Lithofacies with intermediate grain size have considerably lower thickness: 3.5 m (11.5 ft) for
450 muddy sand, and 1.5 m (4.9 ft) for sandy mud. **Lowstand Systems Tract (LST)** – The largest gross-
451 thickness values are recorded in the northern sector (up to 20 m [65 ft] in Figure 7B); in contrast, the
452 LST in the southern region is < 5-meters [< 16 ft] thick. The total volume of LST is 21.8 km³ (5.2
453 mi³; Table 1). Lowstand deposits are entirely of alluvial origin (Table 1): fluvial-channel sand is the
454 dominant facies association (54.5% or 11.9 km³ [2.8 mi³]), with average net-thickness of 11 meters
455 (36 ft); the heterolithic crevasse and levee facies association represents ~8% (1.7 km³ [0.4 mi³]) of
456 the total volume, with an average thickness of 1.3 meters (4.2 ft). About 30% (6.5 km³ [1.6 mi³]) of
457 LST is made up of well-drained floodplain mud, with average net-thickness of 3.3 meters (10.8 ft).
458 The poorly-drained floodplain facies association constitutes 6.8% (1.5 km³ [0.4 mi³]), whereas
459 swamp deposits only compose 0.8% (0.2 km³ [0.5E-1 mi³]), with average net-thicknesses of 1.6 and
460 0.4 meters (5.2 and 1.3 ft), respectively.

461 This systems tract consists predominantly of sand (57.5% or 12.6 km³ [3 mi³]), whereas mud
462 represents 37.2% (or 8.1 km³ [2.0 mi³]). Sandy mud and muddy sand lithofacies form only 5% of the
463 systems tract volume, ca. 1.1 km³ (~0.2 mi³). Sandy intervals also display the largest net-thickness
464 (9.7 m [31.8 ft]), followed by mud (3.7 m [12.1 ft]), muddy sand (1 m [3.3 ft]), and sandy mud (0.8
465 m [2.6 ft]). **Transgressive Systems Tract** (TST) – Relatively narrow, W-E elongated sediment bodies
466 in the central sector of Figure 7C show the maximum gross-thickness (about 15 m [49 ft]).
467 Thicknesses up to 10 meters (~33 ft) characterize the eastern part of the study area, whereas the
468 lowest values (< 5 m [16 ft]) are in the SW. The total volume of TST is 17.2 km³ (4.1 mi³; Table 1).
469 Transgressive deposits are mostly characterized by an estuarine facies assemblage (Bruno et al.,
470 2017). Swamp clay (34% or 5.9 km³ [1.4 mi³]) is the dominant facies association, followed by lagoon
471 (11.5% or 2.0 km³ [0.5 mi³]) and poorly-drained floodplain (11.3% or 1.9 km³ [0.4 mi³] - Table 1)
472 deposits. On the other hand, fluvial and distributary-channel deposits, along with bay-head delta
473 facies comprise almost 25% (ca. 4.2 km³ [1.0 mi³]) of the total volume, with an average thickness of
474 about 4 meters (~13 ft; Table 1). Other channel-related facies associations (i.e., crevasse/levee
475 deposits) represent 8.4% (1.5 km³ [0.4 mi³]) of the entire TST, with an average net-thickness of 1.3
476 meters (4.2 ft; Table 1). Only 1.2% (0.2 km³ [0.5E-1 mi³]) of TST is formed by thin (0.2 m [0.7 ft]),
477 well-drained floodplain facies. The residual 8.8% consists of shallow-marine facies associations:
478 transgressive barrier deposits (5.3% or 0.9 km³ [0.2 mi³]), with average thickness of 1.5 m (4.9 ft);
479 and thin (ca. 0.9 m [2.9 ft]) offshore strata, which make 3.5% (0.6 km³ [0.1 mi³]) of the total systems
480 tract volume (Table 1).

481 Mud is the most abundant lithofacies in this systems tract (Table 2), accounting for 57.8% (10
482 km³ [2.4 mi³]) of the total volume, and with an average net-thickness of 4.7 meters (15.4 ft). Sand
483 represents 29.5% (5.0 km³ [1.2 mi³]), muddy sand 10.4% (1.8 km³ [0.4 mi³]), and sandy mud the
484 remaining 2.3% (0.4 km³ [0.9E-1 mi³]). The average net-thickness is 4.2 m (13.8 ft) for sand, 1.5 m
485 (4.9 ft) for muddy sand, and 0.9 m (2.9 ft) for sandy mud.

486 **Highstand Systems Tract (HST)** – The maximum gross-thickness (up to 30 m [100 ft]) occurs
487 in the eastern regions (Figure 7D). The HST is progressively thinner to the west, down to about 12
488 meters (~ 40 ft). The total volume of HST is 26.7 km³ [6.4 mi³; Table 1]. This systems tract is
489 characterized by significant volumes of delta-front/beach-ridge sand (19.9% or 5.3 km³ [1.3 mi³])
490 and prodelta clay (9.9% or 2.6 km³ [0.6 mi³]; Table 1), with a remarkably high net-thicknesses of
491 10.2 and 6.4 meters (33.5 and 21.0 ft), respectively. Delta-plain deposits, including poorly-drained
492 floodplain, swamp and lagoon facies associations, compose 44.4% (or 14.3 km³ [3.4 mi³]) of the total
493 volume (Table 1). The distributary-channel facies association is more abundant than the fluvial-
494 channel facies (6.6% vs 0.8% or 1.8 vs 0.2 km³ [0.4 vs 0.5E-1 mi³]), with an average net-thickness
495 of 5 meters (16.4 ft). Likewise, distributary-channel-related facies are more abundant than fluvial
496 crevasse-levee deposits (i.e., 5.5% vs 3.5% or 1.5 vs 0.9 km³ [0.4 vs 0.2 mi³]); whereas bay-head-
497 delta sand bodies are quite scarce, accounting for just 0.4% (0.1 km³ [0.2E-1 mi³]) of the total volume
498 (Table 1). The volume of well-drained floodplain deposits is about 9% (ca. 2.4 km³ [0.6 mi³]), with
499 a net-thickness of 2.5 meters (8.2 ft).

500 As in the TST, mud is the predominant lithofacies in the HST, with very high percentages (about
501 60.5% or 16.2 km³ [3.9 mi³] - Table 2). The remaining 39.5% includes sand (23.4% or 6.0 km³ [1.4
502 mi³]), muddy sand (12.5% or 3.5 km³ [0.8 mi³]), and sandy mud (3.6% or 1.0 km³ [0.2 mi³]). The
503 average net-thickness is 8.7 meters (28.5 ft) for mud, and 6.7 m (22 ft) for sand. Average net-
504 thicknesses of 2.4 and 1.3 meters (7.9 and 4.2 ft) are typical of muddy sand and sandy mud,
505 respectively.

506

507 **DISTRIBUTION AND NET-THICKNESS OF SAND**

508 The volume, distribution, and connectivity of sand-rich strata are important parameters for
509 characterizing the performance of not only aquifers but also hydrocarbon reservoirs (e.g., Fogg, 1986;
510 Doust and Omatsola, 1990; Larue and Hovadik, 2006; Galloway and Hobday, 2012; Chamberlain et
511 al., 2013; Willis et al., 2015 and many others). A sequence-stratigraphic approach is extremely useful

512 to set up a preliminary, but detailed geological model to make reliable predictions about spatial
513 distribution of lithofacies and areal extent and connectivity of sand strata.

514 For each systems tract we constructed:

515 - a sand partitioning map, with an associated diagram that reveals statistical trends in sand
516 distribution;

517 - a thickness map, which offers collateral information about the net-thickness of sand deposits.

518 ***Lowstand Systems Tract*** – Within the fully alluvial LST, sediment distribution reveals a well-
519 defined partitioning: the largest amount of sand is observed in the central and northern sectors of the
520 map (Figure 8A), where fluvial-channel deposits cover about two-thirds of the study area (Table 1).
521 The distribution diagram of Figure 8B shows that > 55% of the LST consist of 80–100% sand, 45%
522 of the entire systems tract being composed of 90-100% sand. On the other hand, sand is almost lacking
523 in the southern sector (Figure 8A), where well-drained floodplain deposits are dominant (Figure 6A,
524 B and Table 1). Scattered, narrow coarse-grained sand bodies in this area are elongated in a S-N
525 direction (Figure 8A).

526 Lowstand sandy strata are increasingly thicker in the north (i.e., > 15 m [> 49 ft]), with an
527 average thickness of about 15 m (≈ 49 ft); Figure 8C). In the southern part of the study area, sand
528 bodies are invariably < 5 m (< 16 ft) thick (Figure 8C).

529 From a hydrostratigraphic perspective, LST exhibits a strong vertical lithologic partitioning
530 into: (i) a lower sandy unit composed of amalgamated, laterally extensive (i.e., > 25 km [> 16 mi])
531 wide) fluvial-channel bodies (Figure 6; Table 1) characterized by very high connectivity, as suggested
532 by the highest percentages of sand (Figure 8A, B); and (ii) an upper thick confining unit with less
533 than 50% sand, made up predominantly of laterally continuous, well-drained floodplain muds (Figure
534 6 and Tables 1, 2).

535 ***Transgressive Systems Tract*** - This systems tract consists of scattered sands only (Figure 9A).
536 The widest and thickest sand bodies are localized in the north and follow a west-east orientation. In
537 the western sector, sand bodies develop a distributive pattern to the south-east. Sand deposits have a

538 patchy distribution in the easternmost locations (Figure 9A). The distribution diagram of Figure 9B
539 reveals that only 1.8% of the TST is made up of 90-100% sand. About 25% transgressive deposits
540 include 0-10% sand, and low sand concentrations are quite common (Figure 9B).

541 Sand bodies generally are < 5 meters thick ([< 16 ft]; Figure 9C). Locally, in the northern and
542 central sectors, their thickness attains 10 meters ([33 ft]; Figure 9C).

543 The characteristic spotty distribution of sand bodies and low sand concentrations (Figure 9A,
544 C) imply overall low connectivity, making the TST of scarce interest from an exploration perspective.
545 In particular, sand bodies in the north are interpreted as fluvial or distributary channel facies
546 associations (Figure 6 and Table 1), with a relatively high continuity in downstream direction, but
547 minimal lateral development. In this systems tract, low sand connectivity is also diagnostic of other
548 two facies associations with sand as the prevalent lithofacies (see Table 1):

549 - multi-pronged distributary-channel and bay-head-delta sands, in the central and southern
550 sectors (Figure 9A);

551 - isolated and scattered transgressive barrier deposits in the east (Figure 9A).

552 On the other hand, predominantly fine-grained strata consisting mostly of swamp, poorly-
553 drained floodplain, and lagoon facies associations (Table 1) represent a thick confining unit between
554 the underlying (i.e., lowstand) and overlying (i.e., highstand) potentially permeable deposits.

555 ***Highstand Systems Tract*** – The HST has a general scarcity of sand: the only significant
556 exception is a single coastal sediment body, 5–10 km (3-6 mi) wide and > 30 km (> 19 mi) long,
557 parallel to the modern shoreline (Figure 10A). It is made up of delta-front and beach-ridge facies
558 associations (Table 1). In the coastal sector, HST strata exhibit relatively high sand concentrations,
559 with percentages between 50 and 80%. Seawards, the sand gradually becomes less abundant and
560 wedges out (40-0%). Landwards, narrow-sinusoidal sand bodies (distributary channel facies
561 association) with W-E orientation can be traced within an almost sand-free lithozone (Figure 10A).

562 Within highstand strata, 44.4% of cores record < 10% sand, whereas only 0.1% have 90-100%
563 sand. Sand partitioning is well illustrated by the sand distribution diagram, which shows a negative
564 tendency with a sharp break between the first two deciles (Figure 10B).

565 Laterally extensive coastal sand bodies parallel to the modern shoreline exhibit average
566 thickness of about 10 m (~33 ft), and a maximum value of 15 m (~49 ft) (Figure 10C). In this generally
567 homogeneous sandy lithosome, thick and isolated sand bodies branch out seawards (Figure 10C),
568 most likely representing individual, prograding delta lobes (Amorosi et al., 2017b).

569 The HST shows three prominent hydrostratigraphic components that reflect distinct
570 environments of deposition: the delta plain, largely dominated by swamp, but also by lagoon and
571 well-drained floodplain deposits (i.e., facies associations with mud as the dominant lithofacies; see
572 Table 1); the coastal component, almost entirely characterized by sandy delta-front and beach-ridge
573 facies associations (Table 1); and the prodelta, with its typical fine-grained facies association (Table
574 1). Thick coastal deposits parallel to the modern coastline (Figure 6 and Table 1), with relatively high
575 sand concentration (50-80%) and remarkable lateral continuity (up to 30 km [19 mi]) form a potential
576 aquifer. This sand body transitions laterally into two mud-dominated confining units (i.e.,
577 aquitards/aquicludes): prodelta (seawards) and delta plain (landwards) deposits.

578

579 **HYDRAULIC PARAMETERS, HYDROFACIES AND AQUIFER** 580 **CHARACTERIZATION**

581 Building a reliable hydrostratigraphic model requires that hydraulic parameters of aquifers be
582 incorporated within an accurate stratigraphic framework (Maliva, 2016).

583 The simplified cross-section in Figure 11, transverse to the present shoreline (Figure 1, for
584 location), summarizes the major architectural elements, facies-association and lithofacies
585 distributions, sequence stratigraphy and main hydrostratigraphic components of the study area. The
586 stratigraphic framework and aquifer characterization can be enhanced by hydraulic parameters, such
587 as:

588 - average horizontal hydraulic conductivity (K) values of the main facies associations (see
589 Figure 4), which were lastly framed into the corresponding systems tracts (Figure 11A), K values in
590 Figure 4 are less specific because they refer to the entire LP-H depositional sequence: the same facies
591 may have distinct K values depending on the systems tract.

592 - average transmissivity (T) of the two major permeable units (i.e., lowstand and highstand
593 aquifers; Figure 11B).

594 **Lowstand Systems Tract** - LST deposits have a strong contrast of > 5 orders of magnitude
595 between high-permeability ($K=3.2E-4$ m/s [$10.5E-4$ ft/s]) fluvial-channel sands and low-permeability
596 ($K=9.5E-9$ m/s [$31.2E-9$ ft/s]) well-drained floodplain muds. Isolated crevasse/levee and poorly-
597 drained floodplain facies exhibit low K values, on the order of $8.5E-8$ ($27.9E-8$ ft/s) and $1.2E-8$ m/s
598 ($3.9E-8$ ft/s), respectively (Figure 11A).

599 Owing to the high connectivity of multilateral and multi-story fluvial deposits, the LST includes
600 a major aquifer (Figure 11B) that is widespread in the central and northern sectors of the study area
601 (Figure 8A, C). This aquifer (Upper A1 aquifer of Molinari et al., 2007) has an average transmissivity
602 of $3.5E-3$ m²/s ($\sim 37.7E-3$ ft²/s). It represents a typically confined aquifer, sandwiched between older
603 and younger well-drained floodplain muds (Figure 11B). Fine-grained, low-permeability strata mark
604 the lateral boundary of this aquifer to the south (Figure 11A, B). Unfortunately, lack of data prevented
605 us from reconstructing the aquifer geometry farther north.

606 **Transgressive Systems Tract** - Very low to low permeability typifies most TST strata: poorly-
607 drained floodplain ($K=1.6E-9$ m/s [$5.2E-9$ ft/s]), swamp ($K=8.8E-9$ m/s [$28.9E-9$ ft/s]) and lagoon
608 ($K=1.0E-8$ m/s [$3.2E-8$ ft/s]) facies (Figure 11A). A moderately higher hydraulic permeability
609 ($K=1.9E-7$ m/s [$6.2E-7$ ft/s]) characterizes isolated crevasse channels.

610 The general predominance of low-permeability, fine-grained deposits (Figure 11A), along with
611 the scarce connectivity of distributary-channel and transgressive barrier sand bodies, make the TST
612 a widespread, effective confining unit (i.e., aquitard/aquiclude; Figure 11B). Locally, in the northern

613 sector, individual fluvial-channel bodies may erode into and connect with the underlying LST strata
614 (Figure 11B).

615 ***Highstand Systems Tract*** - HST lagoon and swamp facies associations exhibit similar K values
616 as their transgressive counterparts (Figure 11A). HST Distributary-channel sands are about as
617 permeable as crevasse/levee deposits ($4.1\text{E-}7$ m/s [$13.5\text{E-}7$ ft/s] vs. $4.7\text{E-}7$ m/s [$15.4\text{E-}7$ ft/s],
618 respectively). On the other hand, poorly-drained and well-drained floodplain muds of Holocene age
619 show lower K values ($4.5\text{E-}8$ m/s [$14.7\text{E-}8$ ft/s] and $7.2\text{E-}10$ m/s [$23.6\text{E-}10$ ft/s], respectively) than
620 comparable LST (Late Pleistocene) floodplain facies association (Figure 11A). The average
621 permeability of coastal sand deposits is $5.3\text{E-}6$ m/s ($17.4\text{E-}6$ ft/s); whereas the characteristic K value
622 of fine-grained prodelta facies is two orders of magnitude lower ($2.4\text{E-}8$ m/s [$7.8\text{E-}8$ ft/s]; Figure
623 11A).

624 From a hydrostratigraphic perspective, HST consists of a prominent permeable unit (aquifer)
625 and two adjacent confining sediment bodies (aquitards/aquicludes), as shown in Figure 11B. The HST
626 aquifer comprises laterally extensive coastal sands with moderate to good connectivity effectively
627 perpendicular to the LST aquifer thickness trend (Figures 10A, 11A, B). Its average transmissivity is
628 about $5.4\text{E-}5$ m²/s ($58.1\text{E-}5$ ft²/s), i.e. two orders of magnitude lower than transmissivity in the LST
629 aquifer (Figure 11B). Most likely this is due to the generally smaller grain size of coastal sands
630 relative to the lowstand fluvial channel-belt sand body, and to an abundance of silt/clay intercalations
631 at the transition with prodelta muds (Figures 8A, B, 10A, B; Tables 1, 2). The HST coastal sands crop
632 out continuously along the modern coastal plain, which makes this coastal aquifer unconfined (Figure
633 11B; Molinari et al., 2007).

634

635 **SEQUENCE STRATIGRAPHY: A TOOL FOR GROUNDWATER EXPLORATION**

636 In groundwater exploration, aquifer characterization is traditionally based on a
637 lithostratigraphic approach (sand vs mud), where facies relations are mostly neglected (Ponti et al.,
638 2007). On the other hand, a pure chronometric approach (Pleistocene vs Holocene) may also be

639 inconclusive, as aquifers do not necessarily correspond with chronostratigraphic units (Ehman and
640 Edwards, 2017). This study shows that the application of sequence-stratigraphic concepts can enable
641 accurate characterization and prediction of aquifer geometry, well beyond any lithostratigraphic or
642 chronostratigraphic approach.

643 Figure 12 illustrates the consequences of these three approaches to mapping and interpretation.
644 A lithostratigraphic approach to aquifer characterization in the Po Basin is shown in Figure 12A,
645 which depicts the sand net-thickness of the entire LP-H Sequence. The thickness trends on this map
646 show a vaguely elliptical pattern that is difficult to interpret in terms of depositional environments or
647 from which to make predictions. With the application of a chronostratigraphic approach, the LP-H
648 Sequence map of Figure 12A can be split into two sand thickness maps, representing the Late
649 Pleistocene and Holocene successions, respectively (Figure 12B, C). The pattern of the Late
650 Pleistocene succession is coherent because it portrays a genetically-related fully alluvial system,
651 whereas the pattern of the Holocene succession is less clear. In a sequence-stratigraphic perspective,
652 aimed to examine aquifer architecture on a systems-tract scale, the Holocene succession can be
653 subdivided into a TST map (Figure 12D) and HST map (Figure 12E). This further partition provides
654 more detail and accuracy in an aquifer characterization perspective: coastal sands (i.e., delta front and
655 beach ridge deposits) within HST make an important aquifer that is laterally confined by two low-
656 permeability units (i.e., delta plain and prodelta), and vertically separated from the LST aquifer by
657 the TST aquitard.

658 In addition, as strata geometry and aquifer/aquitard distribution are linked to the geological
659 processes that generated the sedimentary bodies (Ehman and Ponti, 2014), differentiating facies
660 associations provides detailed insights into the character (i.e., permeability, connectivity,
661 heterogeneities) and the spatial extent of aquifers. This type of information can be very useful to
662 groundwater management and aquifer exploitation.

663 At a yet finer scale, recent paleoenvironmental reconstructions at the parasequence-scale from
664 the study area (Amorosi et al., 2017b; Bruno et al., 2017) further reveal the hydrostratigraphic

665 significance of facies relations within each systems tract. The “depositional history” of TST and HST
666 is sketched in Figures 13 and 14, respectively. Parasequences in the TST contain transgressive sands
667 (Figure 13A) that mostly consist of relatively thin (~ 5 m [~ 49 ft]) deposits of fluvial/distributary
668 channel, bay-head delta, and transgressive-barrier facies associations. During the early Holocene, the
669 fluvial environment (Figure 13B) was drowned in response to rapid eustatic rise (Bruno et al., 2017),
670 and was progressively replaced by a mud-dominated estuarine environment, with a predominance of
671 swamp and lagoon facies associations (Figure 13C, D). The minimal aquifer potential of TST sands
672 mostly depends on their low connectivity, which in turn is a function of the geometry of
673 fluvial/distributary channels and of the strongly lenticular shape of transgressive-barrier sand bodies.
674 On the other hand, HST parasequences contain laterally continuous (> 35 km [> 22 mi]) sand deposits,
675 up to 15 m thick (~ 49 ft; Figure 14A), that formed in response to the progradation of wave- (Figure
676 14B, C) and river-dominated (Figure 13D) delta systems and contiguous strand plains (Amorosi et
677 al., 2017b). In the middle-late Holocene parasequences, delta-lobe switching and southerly-directed
678 longshore currents formed a laterally continuous sand body of delta-front and beach-ridge facies
679 associations, parallel to the shoreline (Figure 14A), which represents an important aquifer.

680 In summary, the sequence-stratigraphic approach revealed critical details of subsurface
681 geometry and spatial distribution of lithosomes, with potential hydrostratigraphic implications for
682 groundwater exploration across a range of vertical and lateral scales that other stratigraphic
683 approaches tend to obscure. Sequence stratigraphy provides these improvements by recognizing
684 genetically related strata—this enables accurate prediction of rock/sediment properties using
685 Walther’s Law and process-based models. The sequence-stratigraphic approach is scalable, efficient,
686 and cost-effective, because it reveals the genetically related strata through the geometric relations of
687 the strata themselves and their bounding surfaces (Mitchum et al., 1977).

688

689 **APPLICATIONS TO HYDROCARBON RESERVOIR EVALUATION AND** 690 **MODELING**

691 The data and insights provided by our work can be useful input for realistically modeling the
692 spatial distribution of fluvial and coastal-plain reservoirs and seals. Such models are essential for
693 making reliable estimates of volumes in place, evaluating connectivity, and providing numerical input
694 to flow simulations. Many of these models are based on a hierarchy of stratigraphic elements and
695 reservoir geobodies; they emphasize geologically sound geometric concepts and conditioning data of
696 areal and vertical facies proportions (e.g., Deutsch and Wang, 1996). High-resolution sequence-
697 stratigraphic analysis, such as shown in our work, provides the spatial framework of stratigraphic
698 elements and geologically sound correlation concepts. Detailed mapping within that sequence-
699 stratigraphic framework specifies the distribution and dimensions of the reservoir and seal geobodies
700 (conditioning data). Characterization of the genetically related strata revealed by sequence-
701 stratigraphic analysis provides a tie among depositional environment, facies association, and rock and
702 flow properties (porosity, permeability, transmissivity, conductivity).

703 Based on our work in the LP-H succession of the Po River Plain, facies associations have flow
704 properties that are a function of component facies, depositional environment, and stratigraphic
705 position at the systems-tract scale. A key finding of our work is that certain facies associations have
706 different flow properties between systems tracts and that seemingly homogeneous deposits may
707 exhibit subtle, but consistent changes in permeability across key sequence stratigraphic surfaces. As
708 an example, prodelta muds in the HST are twice as permeable as offshore facies in the TST (Figure
709 11A), likely reflecting more energetic sub-environments and slightly greater grain size.

710 We also observed that the level of stratigraphic hierarchy made a difference to the distribution
711 of reservoir and seal geobodies. Permeability distribution changes vertically and laterally as a
712 function of systems tract and parasequence stacking within the systems tract (Figure 11A). At a finer
713 scale, the dimensions and orientations/trends of high and low permeability sediment bodies vary
714 systematically within parasequences (Figures 13 and 14).

715 We conclude that correlation and mapping based on sequence stratigraphy provide both
716 accurate portrayals of subsurface geometry and spatial distribution of potential reservoirs and seals

717 (or aquifers vs aquitards/aquicludes) and robust predictions of flow properties away from sample
718 control. In contrast, correlation and mapping based on formation tops (i.e., lithostratigraphic method)
719 or an exclusively chronometric approach tend to obscure trends and connectivity of potential flow
720 paths because lithostratigraphic formations commonly span multiple genetically related units; such
721 units typically have widely varying distributions of high and low permeability sediment bodies.

722

723 **CONCLUSIONS**

724 The sequence-stratigraphic approach was applied to Quaternary deposits from the Po River
725 Basin and was used for the aquifer characterization of alluvial (late Pleistocene) and coastal to
726 shallow-marine (Holocene) strata.

727 Stratigraphic analysis of 641 geological tests and 15 continuous cores enabled lithofacies
728 identification, facies analysis and stratigraphic correlations. Sequence-stratigraphic analysis enabled
729 a significantly more refined aquifer characterization than traditional lithostratigraphic or
730 chronostratigraphic methods of stratigraphic correlation.

731 The identification and correlation of the main key surfaces (Sequence Boundary, Transgressive
732 Surface and Maximum Flooding Surface) led to the recognition of a third-order depositional sequence
733 (LP-H depositional sequence) and its internal components (parasequences and systems tracts: LST,
734 TST, and HST). This further subdivision into parasequences and systems tracts provides much higher
735 resolution to the analysis of the investigated strata, especially in terms of aquifer characterization:
736 within each parasequences and systems tract, all strata are genetically related which enables accurate
737 prediction of subsurface geometry and spatial distribution of potential aquifers, aquitards and
738 aquicludes along with intrinsic changes in hydraulic properties trends. The spatial variation (i.e.,
739 heterogeneity) of these properties within a geological succession/formation represents, in fact, one of
740 the most challenging issues in aquifer (and hydrocarbon reservoir) characterization. Since
741 heterogeneity is mostly linked to the depositional history of the strata of interest, we considered facies
742 associations as fundamental architectural units because trends in heterogeneity largely depend on the

743 distribution of the facies associations. Identification of facies associations and analysis of their
744 vertical and lateral relations are powerful tools for environmental reconstructions. These
745 reconstructions can be very useful to infer areal extent and geometries of high vs low permeability
746 geobodies and their corresponding variations of hydraulic parameters, especially from limited site-
747 specific information.

748 The analysis of sand distribution and average net-thickness of sand bodies, along with the
749 accurate hydraulic characterization of individual facies associations allowed the identification of two
750 highly permeable units, vertically separated by low-permeability strata. In particular, the LST
751 includes a ~15 m thick and > 25 km wide, confined aquifer made up of highly interconnected fluvial-
752 channel sand bodies with W-E (along channel) orientation. The TST represents a widespread
753 permeability barrier, being dominated by low-permeability estuarine facies such as swamp, lagoon
754 and poorly-drained floodplain deposits. The overlying HST has the highest percentages of fine-
755 grained sediments but also contains a ~10 m thick and 5-10 km wide, unconfined aquifer parallel to
756 the modern shoreline, comprising delta-front and beach-ridge deposits. The LST aquifer has up to
757 two orders of magnitude higher transmissivity than the HST aquifer, most likely because of its larger
758 grain size, very good size sorting, and characteristic bedding. The different hydraulic characteristics
759 also reflect the distinct stacking pattern of sandy facies that accumulated under low-accommodation
760 (LST) versus high-accommodation (HST) conditions.

761 Facies associations have characteristic ranges and average values of horizontal hydraulic
762 conductivity (i.e., K or permeability). Average facies permeabilities were framed into their related
763 systems tracts, revealing that same facies may have distinct average K values, depending on the
764 systems tract. This statement may have important implications for future aquifer and reservoir
765 modeling.

766 Anisotropy in the x-y plane appears to be driven primarily by erosional boundaries (LST) and
767 by lateral facies transitions (HST). The LST-aquifer is laterally confined by low-permeability
768 floodplain deposits, with a sharp facies change. In contrast, the HST aquifer grades landwards and

769 seawards into muddy estuarine and prodelta deposits, respectively. The predominance of low-
770 permeability facies, makes TST an effective confining unit between LST and HST aquifers.

771 This study shows that sequence stratigraphy can be applied successfully and usefully to
772 Quaternary groundwater studies. This study also shows the utility of a sequence-stratigraphic
773 approach for groundwater surveys carried out in comparable geological settings, especially for
774 limiting the costs linked to preliminary data acquisition. Differentiating depositional environments at
775 the facies association scale, in fact, provides good guidance in “how to connect dots” between data
776 points (i.e., wells), especially when seismic data are scarce or absent. Also, aquifer exploitation can
777 be improved, as both LST and HST aquifers are characterized by fairly predictable areal extent (i.e.,
778 along channel axis or parallel to the shoreline, respectively) and thickness trends as well as well-
779 defined geometries and petrophysical properties.

780 In addition, the parasequence scale of investigation that is possible in studies of shallow aquifers
781 reveals an almost unprecedented level of detailed insight into rock-body dimensions and the potential
782 complexities of hydraulic properties trends deeper in the subsurface. Such insights should be useful
783 for guiding and vetting correlation and mapping of the deep subsurface and for hydrocarbon reservoir
784 modelers, from both a point- and object-based perspective.

785

786

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FIGURE CAPTIONS

1057 Figure 1. Location of the investigated area, with indication of: section traces of Figure 5 (blue
1058 line), of Figure 6 (gray lines), and Figure 11 (black line); spatial distribution and type of data (see
1059 legend) utilized in this study.

1060 Figure 2. (A) Seismic profile showing the subdivision of the Pliocene-Quaternary basin fill into
1061 six (1 to 6) third-order depositional sequences (modified from Regione Emilia-Romagna and ENI-
1062 AGIP, 1998). Seismic unconformities are labeled with letters (A to G); black lines represent major
1063 fault systems. The uppermost depositional sequence (Po Supersynthem, Po Ss) is subdivided into
1064 Lower Po Synthem (L-Po S) and Upper Po Synthem (U-Po S). (B) Schematic cross-section showing
1065 the higher-order transgressive-regressive (T-R) successions identified within U-Po S (modified from
1066 Amorosi, 2016). Hydrostratigraphic interpretation (i.e., aquifer systems) after Molinari et al. (2007)
1067 and Regione Emilia-Romagna and ENI-AGIP (1998).

1068 Figure 3. Example of calibration between core data and piezocone penetration test (CPTU)
1069 profiles. A) Lithostratigraphic log of the reference core used for the calibration; B) CPTU test
1070 showing cone resistance (Q_c), sleeve friction (F_s), pore pressure (U) and friction ratio (FR).
1071 Following Amorosi and Marchi (1999), CPTU parameters were used for lithofacies recognition: sand
1072 (S) invariably shows $Q_c > 5$ MPa and negative U values. In muddy sand (mS) Q_c ranges between 2
1073 and 5 MPa, with low-to-negative U . Sandy mud (sM) displays $Q_c < 2$ MPa with irregular U and FR
1074 profiles. Mud (M) has the lowest Q_c and highest U values; C) Lithofacies recognized after the
1075 calibration process; D) Facies associations identified in the reference core and 1:1 comparison (black
1076 dash line) between lithofacies and facies associations; E) Sequence-stratigraphic interpretation.

1077 Figure 4. Cross plot of the main facies associations vs. hydraulic conductivity (K) values. K
1078 values span more than 7 orders of magnitude. Each facies association has a characteristic range of K
1079 values. There is substantial overlap among low-permeability (clay, silty clay) facies; swamp, lagoon,
1080 poorly-drained floodplain, well-drained floodplain, and offshore/prodelta deposits. A second cluster
1081 is composed of high-permeability sand deposits: fluvial-channel are about two orders of magnitude
1082 more permeable than delta front/beach ridge facies. A third, intermediate cluster of permeability is
1083 represented by crevasse/levee and distributary channel facies associations, which include sandy silt
1084 and silty sand.

1085 Figure 5. Schematic cross-sections (modified from Amorosi et al., 2017b; see Figure 1 for
1086 location, blue line) showing the comparison of two different stratigraphic correlation styles: A)
1087 sequence stratigraphic correlation; B) lithostratigraphic correlation. Lithostratigraphic correlation in
1088 a retrogradational parasequence set leads to an interpretation of a single continuous sand body at the
1089 top of the unit that, in fact, comprises intervals that are not connected, as shown by the sequence-
1090 stratigraphic correlation.

1091 Figure 6. Cross-sections depicting facies architecture and sequence-stratigraphic interpretation
1092 of the Late Pleistocene-Holocene succession in the study area (see Figure 1 for location).

1093 Figure 7. Isopach maps showing the gross-thickness of: (A) Late Pleistocene-Holocene
1094 depositional sequence; (B) lowstand systems tract (LST); (C) transgressive systems tract (TST); (D)
1095 highstand systems tract (HST). Systems-tract-scale maps (B, C, D) portray genetically related strata
1096 and are more readily interpreted in terms of depositional environments and conditions.

1097 Figure 8. Sand distribution and net-thickness of sand (S) in the lowstand systems tract (LST).
1098 (A) Areal distribution of sand. (B) Graph showing statistical trends of sand distribution: on the x-axis
1099 is amount of sand (S%); on the y-axis is LST total volume (Vt%). (C) Isopach map showing the net-
1100 thickness of LST sand bodies. In the northern sector of the study area, LST consists of highly
1101 connected (~80-100% sand), up to 15 m (> 49 ft) thick fluvial sands. Whereas the southern sector has
1102 a very small proportion of thin sand bodies, and a predominance of well-drained floodplain facies.

1103 Figure 9. Sand distribution and net-thickness of sand (S) in the transgressive systems tract
1104 (TST). Keys as in Figure 8. TST is characterized by scattered, < 5 m thick (< 16 ft) and poorly
1105 connected sand bodies. The TST consists predominantly of fine-grained deposits of swamp, lagoon
1106 and poorly-drained floodplain (Table 1).

1107 Figure 10. Sand distribution and net-thickness of sand (S) in the highstand systems tract (HST).
1108 Keys as in Figure 8. Relatively high sand concentration (50-80% sand) is recorded parallel to the
1109 modern shoreline, beneath the modern coastal plain, where laterally extensive delta-front/beach-ridge
1110 sand bodies are > 15 m (> 50 ft) thick. Sand percentage and thickness decrease landwards within
1111 swamp, lagoon and well-drained floodplain deposits; and seawards, within prodelta muds.

1112 Figure 11. Schematic cross-sections (see Figure 1 for location, black line) displaying the major
1113 architectural elements and sequence-stratigraphic interpretation (LST, TST, HST) of the study units,
1114 with hydraulic parameters for aquifer characterization: (A) mean permeability (i.e., K) of major facies
1115 associations, and (B) mean transmissivity (i.e., T) of lowstand and highstand aquifers.

1116 Figure 12. Isopach maps illustrating the sand net-thickness of: (A) the Late Pleistocene-
1117 Holocene depositional sequence; (B) Late Pleistocene and (C) Holocene age intervals; (D)
1118 transgressive systems tract-TST and (E) highstand systems tract-HST. The transition from the

1119 lithostratigraphic (A) to chronostratigraphic (B-C) and sequence-stratigraphic (D-E) approach marks
1120 a progressive increase in stratigraphic resolution. Isopach maps in (D) and (E) clearly outline the
1121 geometries of estuarine versus coastal sand bodies in the TST and HST, respectively.

1122 Figure 13. Depositional history of TST at the parasequence-scale. A) Sand (S) distribution and
1123 net-thickness (black lines; m=meters) within TST. B) Early stages of transgression are characterized
1124 by alluvial sediments progressively onlapped by poorly-drained floodplain muds. C) Formation of an
1125 estuary (Bruno et al., 2017), dominated by swamp and lagoon facies associations. D) Late stages of
1126 transgression: maximum landward migration of estuarine facies. Note that sand distribution and
1127 geometry of sedimentary bodies shown in A) are the result of the TST depositional history
1128 summarized in B), C), and D).

1129 Figure 14. Depositional history of HST at the parasequence-scale. A) Sand (S) distribution and
1130 net-thickness (black lines; m=meters) within HST. B) Parasequence 4 (P4) represents early-highstand
1131 progradation of a wave-dominated system. Subsequent river avulsion generates delta-lobe switching
1132 in P5 (modified from Amorosi et al., 2017b). C) Further progradation of delta systems due to delta-
1133 lobe switching and transition from a wave- (P6) to a river-dominated (P7) system. D) Late-highstand:
1134 modern Po Delta formation (P8). Note that sand distribution, net-thickness in HST (A) and its overall
1135 aquifer potential are closely linked to the depositional history sketched in B), C), and D).