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

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ABSTRACT

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

Volumetric assessments, sand-distribution mapping, hydraulic characterization of facies, and spatial variations of hydraulic parameters revealed two aquifer systems (LST, HST) vertically separated by an aquitard (TST). The LST aquifer consists of amalgamated fluvial sands (average transmissivity: 3.5E-3 m^2/s [37.7E-3 ft^2/s]) with considerable width (> 25 km [> 16 mi]) preferentially

elongated downstream. The widespread TST permeability barrier is dominated volumetrically (~57%) by very low-permeability estuarine deposits. The HST aquifer (average transmissivity: 5.4E-5 m^2/s [58.1E-5 ft^2/s]) is 5-10 km (~ 3-6 mi) wide, elongated parallel to the modern shoreline and perpendicular to the LST aquifer.

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

INTRODUCTION

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

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

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

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

The study area (~1,900 km^2 [~730 mi^2]) is located south of the modern Po River, between the city of Ferrara and the Adriatic Sea (Figure 1). The abundance of closely-spaced geological tests (Figure 1) and a well-established chronostratigraphic framework from previous studies (i.e., Amorosi et al., 2017a, b; Bruno et al., 2017; Campo et al., 2017) make this sector an appealing site to develop a hydrostratigraphic approach.

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

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

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

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

Heterogeneity (i.e., spatial variation of hydraulic properties) represents one of the most challenging variables in aquifer (and hydrocarbon reservoir) characterization, and its origin is mostly inherent to the depositional history of the strata of interest (Maliva, 2016). The hydraulic conductivity of siliciclastic deposits largely depends on grain size, sorting and matrix content, which in turn are a function of the source area (i.e., mineralogic composition), transport processes, and hydrodynamic conditions within the depositional environment. Interpretation of depositional processes and environmental settings is difficult if stratigraphic subdivisions are based only on basic lithologic descriptions (conventional lithostratigraphic approach), especially when the dataset is largely composed by cores. On the other hand, the analysis of vertical facies relations (following Walther's law, 1894) and the identification of facies associations (Collinson, 1969; Reading, 2009) allows reliable environmental reconstructions that can be useful for predicting spatial variations of hydraulic conductivity (and its related parameters) from limited site-specific information.

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

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

GEOLOGICAL SETTING

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

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

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

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

Despite the use of a non-uniform terminology and different scales and methods of investigation, previous studies had the merit of identifying aquifer groups at the scale of the entire Po Basin. However, by choosing the abrupt lithological changes from laterally extensive and amalgamated fluvial-channel bodies to overlain muddy units as key surfaces for stratigraphic subdivisions, they did not account for the importance of discontinuities in basin-fill architecture and obscured genetic relations of strata. A "classic" sequence stratigraphic approach, and in particular, the recognition and mapping of sequence boundaries (red lines, Figure 2B), enables a clear recognition and compartmentalization of coarse-grained sedimentary bodies (aquifers) within mud-prone intervals (aquitards), allowing the identification of depositional sequences and more reliable predictions of the spatial distribution of aquifers.

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

METHODS

Database

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

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

In the study area (Figure 1), the average test spacing is 0.5-1 km (0.3-0.6 mi). More specifically, we used 102 core descriptions (average depth 45 m [~147 ft]), including information about grain size, color, pedogenic features, accessory materials (e.g., roots, peats, vegetal fragments, bioturbation, carbonate nodules), pocket penetration values and, in a few cases, radiocarbon dates and permeability tests.

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

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

Lithofacies identification and characterization

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

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

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

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

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

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

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

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

Hydraulic parameters

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

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

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

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

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

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

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

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

- ***T=K*h***, where

'***T***' (m^2/s) is transmissivity; '***K***' (m/s) is the average horizontal hydraulic conductivity of facies associations; and '***h***' is the average net-thickness of the corresponding facies association within LST, TST, and HST (see Table 1).

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

Sequence-stratigraphic approach

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

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

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

The sequence-stratigraphic approach is particularly useful in subdividing the broader scale T-R 'cycles' to build detailed maps. This approach explicitly recognizes a hierarchy of flooding/transgressive surfaces of varying significance and extent. Within a single depositional sequence, there are two major flooding/transgressive surfaces: one at the top of the lowstand systems tract, and the other at the top of the transgressive systems tract (maximum-flooding surface). Between these two major surfaces, there commonly are numerous other flooding/transgressive surfaces of smaller extent that bound parasequences in the transgressive systems tract (Figure 5A). The potential for confusing which surface is of what extent is significant and miscorrelation is common in regional studies, especially if the data used to correlate are widely spaced. The sequence-stratigraphic approach, by focusing attention on the stratal hierarchy helps avoid such errors.

Chronological data and stratigraphic mapping

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

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

- three-dimensional lithofacies and facies-association correlation through the construction of a grid of cross-sections;
- sequence-stratigraphic analysis, i.e. identification and correlation of major stratigraphic surfaces (SB, TS, and MFS);
- gross-thickness mapping of the LP-H Sequence and of its component systems tracts (LST, TST, and HST);
- quantitative volumetric (km^3) estimates of the LP-H Sequence, LST, TST, and HST (Table 1) in areas defined by polygons, based on the stratigraphic position of bounding surfaces;
- quantitative assessments of volumetric percentages and net-thickness of distinct lithofacies and facies associations within the LP-H Sequence, and across systems tracts (LST, TST, and HST; Tables 1, 2). All data-points available from the database (Figure 1) were analyzed. The construction of discrete templates (i.e., lithofacies, facies associations etc..) led to the quantification, for each data-point, of the corresponding percentage and net-thickness of lithofacies and facies associations within the selected stratigraphic interval. In order to provide a more significant spatial distribution of the data, given the average test spacing of 0.5-1 km (0.3-0.6 mi; see Figure 1), we considered 1 data-point/square kilometer (0.4 square mile). On the basis of hundreds

of equally-spaced data measurements, we calculated the arithmetic mean in terms of volumetric percentages (%) and net-thicknesses (m) of lithofacies and facies associations within the LP-H Sequence and in each systems tract (Tables 1, 2);

- volumetric estimation (km^3) of lithofacies and facies associations for the LP-H Sequence and its component systems tracts (LST, TST and HST), on the basis of total sediment volumes and volumetric percentages of lithofacies and facies associations, respectively (Tables 1, 2).
- evaluation and mapping of sand distribution within each systems tract (i.e., LST, TST, and HST). Identical procedures as those utilized for building gross net-thickness maps;
- sand net-thickness mapping of the LP-H Sequence, LP and H intervals, and systems tracts (LST, TST, and HST).

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

LATE PLEISTOCENE-HOLOCENE SEQUENCE STRATIGRAPHY

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

Based on these high-resolution studies, we constructed a three-dimensional framework across the study area. We include here three cross-sections to depict key aspects of the facies architecture and sequence stratigraphy of the Late Pleistocene-Holocene Sequence (Figure 6). Transects A and B run parallel to the present shoreline (Figure 1), across alluvial (Figure 6A) and coastal (Figure 6B) deposits, respectively. A transverse profile is shown in Figure 6C.

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

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

The Transgressive Surface (TS) is interpreted at the widespread and abrupt facies change from aggradational, well-drained LP floodplain deposits (LST) to retrogradational, poorly-drained and organic-matter-rich estuarine sediments of Holocene age (Figure 6A, C); it corresponds to the weakly-developed Inceptisol dated to ca. 12.6 ky BP (i.e., Younger Dryas paleosol of Amorosi et al., 2017a). As a whole, the Transgressive Systems Tract (TST) shows a diagnostic deepening-upward, retrogradational trend from basal, poorly-drained alluvial facies to shallow-marine deposits. At proximal locations, the TST is poorly preserved. Small-sized fluvial bodies are locally associated with the Younger Dryas paleosol (i.e., TS), as shown in Figure 6.

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

QUANTITATIVE ASSESSMENT OF LITHOFACIES AND FACIES ASSOCIATIONS

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

Average volumetric percentage (%), volume estimation (km^3), and average net-thickness (m) of main facies associations (Table 1) and lithofacies (Table 2) were calculated for the entire LP-H depositional sequence and for each systems tract, along with total sediment volumes (Table 1). Gross-thickness maps (Figure 7) were also built as a support to interpreting the quantitative data.

Late Pleistocene-Holocene (LP-H) Depositional Sequence – The gross-thickness map (Figure 7A) shows the largest values of about 50 m (~165 ft) in the NE sector of the study area, whereas the lowest thickness is recorded in the SW (~16 m [~52 ft]). The total volume of the LP-H Sequence is 65.7 km^3 (15.8 mi^3; Table 1). In terms of facies associations, volumetrically abundances (> 10% of total volume) at the sequence-scale are: fluvial channel sands (23.7% or 15.6 km^3 [~3.7 mi^3]), well-drained floodplain muds (11.4% or 7.5 km^3 [1.8 mi^3]), swamp clays (22.2% or 14.6 km^3 [3.5 mi^3]), and coastal (transgressive-barrier, delta-front, and beach-ridge) sands (10.9% or 7.1 km^3 [1.7 mi^3]; Table 1).

About 50% (~32.9 km^3 [~7.9 mi^3]) of the entire depositional sequence consists of mud (Table 2). Sand (39.2% or 25.1 km^3 [~6 mi^3]) and muddy sand (9.5% or 6.2 km^3 [~1.5 mi^3]), taken together, form slightly less of the remaining 50%, whereas sandy mud accounts for just 2.3% (1.5 km^3 [~0.4 mi^3]) of the total volume. Mud and sand lithofacies show a comparable net-thickness of about 16 meters (~52 ft). Lithofacies with intermediate grain size have considerably lower thickness: 3.5 m (11.5 ft) for muddy sand, and 1.5 m (4.9 ft) for sandy mud. ***Lowstand Systems Tract*** (LST) – The largest gross-thickness values are recorded in the northern sector (up to 20 m [~65 ft] in Figure 7B); in contrast, the LST in the southern region is < 5-meters [< 16 ft] thick. The total volume of LST is 21.8 km^3 (5.2 mi^3; Table 1). Lowstand deposits are entirely of alluvial origin (Table 1): fluvial-channel sand is the dominant facies association (54.5% or 11.9 km^3 [2.8 mi^3]), with average net-thickness of 11 meters (36 ft); the heterolithic crevasse and levee facies association represents ~8% (1.7 km^3 [0.4 mi^3]) of the total volume, with an average thickness of 1.3 meters (4.2 ft). About 30% (6.5 km^3 [~1.6 mi^3]) of LST is made up of well-drained floodplain mud, with average net-thickness of 3.3 meters (10.8 ft). The poorly-drained floodplain facies association constitutes 6.8% (1.5 km^3 [~0.4 mi^3]), whereas swamp deposits only compose 0.8% (0.2 km^3 [0.5E-1 mi^3]), with average net-thicknesses of 1.6 and 0.4 meters (5.2 and 1.3 ft), respectively.

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

Mud is the most abundant lithofacies in this systems tract (Table 2), accounting for 57.8% (10 km^3 [2.4 mi^3]) of the total volume, and with an average net-thickness of 4.7 meters (15.4 ft). Sand represents 29.5% (5.0 km^3 [1.2 mi^3]), muddy sand 10.4% (1.8 km^3 [~0.4 mi^3]), and sandy mud the remaining 2.3% (0.4 km^3 [0.9E-1 mi^3]). The average net-thickness is 4.2 m (13.8 ft) for sand, 1.5 m (4.9 ft) for muddy sand, and 0.9 m (2.9 ft) for sandy mud.

Highstand Systems Tract (HST) – The maximum gross-thickness (up to 30 m [~100 ft]) occurs in the eastern regions (Figure 7D). The HST is progressively thinner to the west, down to about 12 meters (~40 ft). The total volume of HST is 26.7 km^3 [6.4 mi^3; Table 1]. This systems tract is characterized by significant volumes of delta-front/beach-ridge sand (19.9% or 5.3 km^3 [~1.3 mi^3]) and prodelta clay (9.9% or 2.6 km^3 [~0.6 mi^3]; Table 1), with a remarkably high net-thicknesses of 10.2 and 6.4 meters (33.5 and 21.0 ft), respectively. Delta-plain deposits, including poorly-drained floodplain, swamp and lagoon facies associations, compose 44.4% (or 14.3 km^3 [3.4 mi^3]) of the total volume (Table 1). The distributary-channel facies association is more abundant than the fluvial-channel facies (6.6% vs 0.8% or 1.8 vs 0.2 km^3 [~0.4 vs 0.5E-1 mi^3]), with an average net-thickness of 5 meters (16.4 ft). Likewise, distributary-channel-related facies are more abundant than fluvial crevasse-levee deposits (i.e., 5.5% vs 3.5% or 1.5 vs 0.9 km^3 [~0.4 vs 0.2 mi^3]); whereas bay-head-delta sand bodies are quite scarce, accounting for just 0.4% (0.1 km^3 [0.2E-1 mi^3]) of the total volume (Table 1). The volume of well-drained floodplain deposits is about 9% (ca. 2.4 km^3 [~0.6 mi^3]), with a net-thickness of 2.5 meters (8.2 ft).

As in the TST. mud is the predominant lithofacies in the HST, with very high percentages (about 60.5% or 16.2 km^3 [~3.9 mi^3] - Table 2). The remaining 39.5% includes sand (23.4% or 6.0 km^3 [1.4 mi^3]), muddy sand (12.5% or 3.5 km^3 [0.8 mi^3]), and sandy mud (3.6% or 1.0 km^3 [0.2 mi^3]). The average net-thickness is 8.7 meters (28.5 ft) for mud, and 6.7 m (22 ft) for sand. Average net-thicknesses of 2.4 and 1.3 meters (7.9 and 4.2 ft) are typical of muddy sand and sandy mud, respectively.

DISTRIBUTION AND NET-THICKNESS OF SAND

The volume, distribution, and connectivity of sand-rich strata are important parameters for characterizing the performance of not only aquifers but also hydrocarbon reservoirs (e.g., Fogg, 1986; Doust and Omatsola, 1990; Larue and Hovadik, 2006; Galloway and Hobday, 2012; Chamberlain et al., 2013; Willis et al., 2015 and many others). A sequence-stratigraphic approach is extremely useful to set up a preliminary, but detailed geological model to make reliable predictions about spatial distribution of lithofacies and areal extent and connectivity of sand strata.

For each systems tract we constructed:

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

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

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

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

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

Transgressive Systems Tract **-** This systems tract consists of scattered sands only (Figure 9A). The widest and thickest sand bodies are localized in the north and follow a west-east orientation. In the western sector, sand bodies develop a distributive pattern to the south-east. Sand deposits have a patchy distribution in the easternmost locations (Figure 9A). The distribution diagram of Figure 9B reveals that only 1.8% of the TST is made up of 90-100% sand. About 25% transgressive deposits include 0-10% sand, and low sand concentrations are quite common (Figure 9B).

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

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

- multi-pronged distributary-channel and bay-head-delta sands, in the central and southern sectors (Figure 9A);
- isolated and scattered transgressive barrier deposits in the east (Figure 9A).

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

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

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

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

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

HYDRAULIC PARAMETERS, HYDROFACIES AND AQUIFER CHARACTERIZATION

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

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

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

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

Lowstand Systems Tract - LST deposits have a strong contrast of > 5 orders of magnitude between high-permeability (K=3.2E-4 m/s [10.5E-4 ft/s]) fluvial-channel sands and low-permeability (K=9.5E-9 m/s [31.2E-9 ft/s]) well-drained floodplain muds. Isolated crevasse/levee and poorly-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 (3.9E-8 ft/s), respectively (Figure 11A).

Owing to the high connectivity of multilateral and multi-story fluvial deposits, the LST includes a major aquifer (Figure 11B) that is widespread in the central and northern sectors of the study area (Figure 8A, C). This aquifer (Upper A1 aquifer of Molinari et al., 2007) has an average transmissivity of 3.5E-3 m^2/s (~37.7E-3 ft^2/s). It represents a typically confined aquifer, sandwiched between older and younger well-drained floodplain muds (Figure 11B). Fine-grained, low-permeability strata mark the lateral boundary of this aquifer to the south (Figure 11A, B). Unfortunately, lack of data prevented us from reconstructing the aquifer geometry farther north.

Transgressive Systems Tract - Very low to low permeability typifies most TST strata: poorly-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 (K=1.0E-8 m/s [3.2E-8 ft/s]) facies (Figure 11A). A moderately higher hydraulic permeability (K=1.9E-7 m/s [6.2E-7 ft/s]) characterizes isolated crevasse channels.

The general predominance of low-permeability, fine-grained deposits (Figure 11A), along with the scarce connectivity of distributary-channel and transgressive barrier sand bodies, make the TST a widespread, effective confining unit (i.e., aquitard/aquiclude; Figure 11B). Locally, in the northern sector, individual fluvial-channel bodies may erode into and connect with the underlying LST strata (Figure 11B).

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

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

SEQUENCE STRATIGRAPHY: A TOOL FOR GROUNDWATER EXPLORATION

In groundwater exploration, aquifer characterization is traditionally based on a lithostratigraphic approach (sand vs mud), where facies relations are mostly neglected (Ponti et al., 2007). On the other hand, a pure chronometric approach (Pleistocene vs Holocene) may also be inconclusive, as aquifers do not necessarily correspond with chronostratigraphic units (Ehman and Edwards, 2017). This study shows that the application of sequence-stratigraphic concepts can enable accurate characterization and prediction of aquifer geometry, well beyond any lithostratigraphic or chronostratigraphic approach.

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

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

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

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

APPLICATIONS TO HYDROCARBON RESERVOIR EVALUATION AND MODELING

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

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

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

We conclude that correlation and mapping based on sequence stratigraphy provide both accurate portrayals of subsurface geometry and spatial distribution of potential reservoirs and seals (or aquifers vs aquitards/aquicludes) and robust predictions of flow properties away from sample control. In contrast, correlation and mapping based on formation tops (i.e., lithostratigraphic method) or an exclusively chronometric approach tend to obscure trends and connectivity of potential flow paths because lithostratigraphic formations commonly span multiple genetically related units; such units typically have widely varying distributions of high and low permeability sediment bodies.

CONCLUSIONS

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

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

The identification and correlation of the main key surfaces (Sequence Boundary, Transgressive Surface and Maximum Flooding Surface) led to the recognition of a third-order depositional sequence (LP-H depositional sequence) and its internal components (parasequences and systems tracts: LST, TST, and HST). This further subdivision into parasequences and systems tracts provides much higher resolution to the analysis of the investigated strata, especially in terms of aquifer characterization: within each parasequences and systems tract, all strata are genetically related which enables accurate prediction of subsurface geometry and spatial distribution of potential aquifers, aquitards and aquicludes along with intrinsic changes in hydraulic properties trends. The spatial variation (i.e., heterogeneity) of these properties within a geological succession/formation represents, in fact, one of the most challenging issues in aquifer (and hydrocarbon reservoir) characterization. Since heterogeneity is mostly linked to the depositional history of the strata of interest, we considered facies associations as fundamental architectural units because trends in heterogeneity largely depend on the distribution of the facies associations. Identification of facies associations and analysis of their vertical and lateral relations are powerful tools for environmental reconstructions. These reconstructions can be very useful to infer areal extent and geometries of high vs low permeability geobodies and their corresponding variations of hydraulic parameters, especially from limited site-specific information.

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

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

Anisotropy in the x-y plane appears to be driven primarily by erosional boundaries (LST) and by lateral facies transitions (HST). The LST-aquifer is laterally confined by low-permeability floodplain deposits, with a sharp facies change. In contrast, the HST aquifer grades landwards and seawards into muddy estuarine and prodelta deposits, respectively. The predominance of low-permeability facies, makes TST an effective confining unit between LST and HST aquifers.

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

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

REFERENCES CITED

AGIP Mineraria, 1959, Campi gassiferi padani, *in* Atti del Convegno su Giacimenti Gassiferi dell'Europa Occidentale, Milano, Accademia Nazionale dei Lincei ed Ente Nazionale Idrocarburi (ENI), 2, p. 45-497.

Amorosi, A., and N. Marchi, 1999, High-resolution sequence stratigraphy from piezocone tests: an example from the Late Quaternary deposits of the SE Po Plain: Sedimentary Geology, v. 128, p. 69-83.

Amorosi, A., M. L. Colalongo, F. Fiorini, F. Fusco, G. Pasini, S. C. Vaiani, and G. Sarti, 2004, Palaeogeographic and palaeoclimatic evolution of the Po Plain from 150-ky core records: Global and Planetary Change, v. 40, p. 55-78.

Amorosi, A., M. Pavesi, M. Ricci Lucchi, G. Sarti, and A. Piccin, 2008, Climatic signature of cyclic fluvial architecture from the Quaternary of the central Po Plain, Italy: Sedimentary Geology, v. 209, p. 58-68.

Amorosi, A., and M. Pavesi, 2010, Aquifer stratigraphy from the middle-late Pleistocene succession of the Po Basin: Memorie Descrittive della Carta Geologica d'Italia, v. 15, p. 7-20.

Amorosi, A., L. Bruno, B. Campo, and A. Morelli, 2015, The value of pocket penetration tests for the high-resolution paleosol stratigraphy of late Quaternary deposits: Geological Journal, v. 50, p. 670-682.

Amorosi, A., V. Maselli, and F. Trincardi, 2016, Onshore to offshore anatomy of a late Quaternary source-to-sink system (Po Plain-Adriatic Sea, Italy): Earth-Science Reviews, v. 153, p. 212-237, doi:10.1016/j.earscirev.2015.10.010.

Amorosi, A., L. Bruno, D. M. Cleveland, A. Morelli, and W. Hong, 2017a, Paleosols and associated channel-belt sand bodies from a continuously subsiding late Quaternary system (Po Basin, Italy): New insights into continental sequence stratigraphy: Geological Society of America Bulletin, v. 129, p. 449-463, doi: 10.1130/B31575.1.

Amorosi, A., L. Bruno, B. Campo, A. Morelli, V. Rossi, D. Scarponi, W. Hong, K. M. Bohacs, and T. M. Drexler, 2017b, Global sea-level control on local parasequence architecture from the Holocene record of the Po Plain, Italy: Marine and Petroleum Geology, v. 87, p. 99-111, doi: 10.1016/j.marpetgeo.2017.01.020.

Antonellini, M., P. Mollema, B. M. S. Giambastiani, K. Bishop, L. Caruso, A. Minchio, L. Pellegrini, M. Sabia, E. Ulazzi, and G. Gabbianelli, 2008, Salt water intrusion in the coastal aquifer of the southern Po Plain, Italy: Hydrogeology Journal, v. 16, p. 1541-1556.

Antonioli, F., L. Ferranti, A. Fontana, A. Amorosi, A. Bondesan, C. Braitenberg, A. Dutton, G. Fontolan, S. Furlani, K. Lambeck, G. Mastronuzzi, C. Monaco, G. Spada, and P. Stocchi, 2009, Holocene relative sea-level changes and vertical movements along the Italian coastline: Quaternary International, v. 221, p. 37-51.

Bakker, M., 2006, Cone penetration tests (CPT), *in* R. Kirsch, H. M. Rumpel, W. Scheer, H. Wiederhold, eds., Groundwater Resources in Buries Valleys: A challenge for Geosciences: Hannover, Leibniz Institute for Applied Geosciences, p. 123-126.

Begemann, H. K. S. 1965, The friction jacket cone as an aid in determining the soil profile: Proceedings of the 6th International Conference on Soil Mechanics and Foundation Engineering, Montreal, September, v. 50, p. 17-20.

Bersezio, R., A. Bini, and M. Giudici, 1999, Effects of sedimentary heterogeneity on groundwater flow in a Quaternary pro-glacial delta environment: joining facies analysis and numerical modeling: Sedimentary Geology, v. 129, p. 327-344.

Bersezio, R., F. Pavia, M. Baio, A. Bini, F. Felletti, and C. Rodondi, 2004, Aquifer architecture of the Quaternary alluvial succession of the southern lambro basin (Lombardy-Italy): Il Quaternario, v., 17, p. 361-378.

Bersezio, R., M. Giudici, and M. Mele, 2007, Combining sedimentological and geophysical data for high-resolution 3-D mapping of fluvial architectural elements in the Quaternary Po plain (Italy): Sedimentary Geology, v., 202, p. 230-248.

Bonzi, L., L. Calabrese, P. Severi, and V. Vincenzi, 2010, L'acquifero freatico costiero della regione Emilia-Romagna: modello geologico e stato di salinizzazione: Il Geologo dell'Emilia Romagna, v. 39, p. 21-34.

Bruno, L., K. M. Bohacs, B. Campo, T. M. Drexler, V. Rossi, I. Sammartino, D. Scarponi, W. Hong, and A. Amorosi, 2017, Early Holocene transgressive palaeogeography in the Po coastal plain (Northern Italy): Sedimentology, v. 64(7), p. 1792-1816, doi.org/10.1111/sed.12374.

Campo, B., A. Amorosi, and L. Bruno, 2016, Contrasting alluvial architecture of late Pleistocene and Holocene deposits along a 120-km transect from the central Po Plain (northern Italy): Sedimentary Geology, v. 341, p. 265-275.

Campo, B., A. Amorosi, and S. C. Vaiani, 2017, Sequence stratigraphy and late Quaternary paleoenvironmental evolution of the Northern Adriatic coastal plain (Italy): Palaeogeography, Palaoclimatology, Palaeoecology, v. 466, p. 265-278.

Chamberlain, E. L., J. S. Hanor, and F. T. C. Tsai, 2013, Sequence stratigraphic characterization of the Baton Rouge aquifer system, southeastern Louisiana: Gulf Coast Association of Geological Societies, v. 63, p. 125-136.

Collinson, J. D., 1969, The sedimentology of the Grindslow Shales and the Kinderscout Grit: a deltaic complex in the Namurian of northern England: Journal of Sedimentary Research, v. 39, p. 194-221.

Dalla, S., M. Rossi, M. Orlando, C. Visentin, R. Gelati, M. Gnaccolini, G. Papani, A. Belli, U. Biffi, and D. Citrullo, 1992, Late Eocene-Tortonian tectono-sedimentary evolution in the western part of the Padan basin (northern Italy): Paleontologia y Evolució, v. 24–25, p. 341-362.

Davis, J. M., R. C. Lohman, F. M. Phillips, J. L. Wilson, and D. M. Love, 1993, Architecture of the Sierra Ladrones Formation, central New Mexico: Depositional controls on the permeability correlation structure: Geological Society of America Bulletin, v. 105, p. 998–1007.

Deutsch, C.V., and L. Wang, 1996, Hierarchical object-based stochastic modeling of fluvial reservoirs: Mathematical Geology, v. 28 (7), p.857-880.

Dondi, L., and M. G. D'Andrea, 1986, La Pianura Padana e Veneta dall'Oligocene superiore al Pleistocene: Giornale di Geologia, v. 48, p. 197-225.

Doust, H., and E. Omatsola, 1990, Niger Delta, *in* Edwards, J. D. and Santogrossi P. A. eds., Divergent/Passive Margin Basins: AAPG Memoir 48, p. 201–238.

Edwards, B. D., 2009, Introduction to Southern California's coastal groundwater basins and aquifer systems: Geological Society of America Special Papers, v. 454, p. 317-318, doi: 10.1130/2009.2454(5.1).

Edwards, B. D., R. T. Hanson, E. G. Reichard, and T. A. Johnson, 2009a, Characteristics of Southern California coastal aquifer systems: Geological Society of America Special Papers, v. 454, p. 319-344, doi: 10.1130/2009.2454(5.2).

Edwards, B. D., K. D. Ehman, , D. J. Ponti, , E. G. Reichard, , J. C. Tinsley, R. J. Rosenbauer, and M. Land, 2009b, Stratigraphic controls on saltwater intrusion in the Dominguez Gap area of coastal Los Angeles: Geological Society of America Special Papers, v. 454, p. 375-395, doi: 10.1130/2009.2454(5.4).

Ehman, K. D., and B. D. Edwards, 2014, Sequence Stratigraphic Framework of Upper Pliocene to Holocene Sediments of the Los Angeles Basin, California: Pacific Section SEPM Book 112, Studies on Pacific Region Stratigraphy, 47 p.

Ehman, K. D., and B. D. Edwards, 2017, Defining Aquifer Architecture Using Seismic and Sequence Stratigraphy in the Los Angeles Basin, California: a Foundation for Future Assessment and Management of Groundwater Resources: Search and Discovery Article #80599, AAPG Datapages.

Felletti, F., R. Bersezio, and M. Giudici, 2006, Geostatistical simulation and numerical upscaling, to model ground-water flow in a sandy-gravel, braided river, aquifer analogue: Journal of Sedimentary Research, v., 76, p.1215-1229.

Filippini, M., C. Stumpp, I. Nijenhuis, H. H. Richnow, and A. Gargini, 2015, Evaluation of aquifer recharge and vulnerability in an alluvial lowland using environmental tracers: Journal of Hydrology, v. 529, p.1657-1668.

Filippini, M., A. Amorosi, B. Campo, S. Herrero-Martìn, I. Nijenhuis, B. L. Parker, and A. Gargini, 2016, Origin of VC-only plumes from naturally enhanced dechlorination in a peat-rich hydrogeologic setting: Journal of contaminant hydrology, v. 192, p.129-139.

Fogg, G. E., 1986, Groundwater flow and sand body interconnectedness in a thick multiple-aquifer system: Water Resources Research, v. 22, p. 679-694.

Gargini, A., M. Pasini, I. Maccanti, A. Messina, L. Piccinini, A. Zanella, F. Biavati, and I. Villani, 2003, Nuovo piano urbanistico di Ferrara: Supporto tecnico idrogeologico alla procedura di valutazione e sostenibilità ambientale, zona Ferrara Nord-Pontelagoscuro, Relazione 1/03.01°, 34 p.

Galloway, W. E., 1989, Genetic stratigraphic sequences in basin analysis I: architecture and genesis of flooding-surface bounded depositional units, AAPG Bulletin, v. 73, p. 125-142.

Galloway, W. E., and Jr. J. M. Sharp, 1998, Characterizing aquifer heterogeneity within terrigenous clastic depositional systems, *in* Fraser G. S. and Davis J. M. eds., Hydrogeologic Models of Sedimentary Aquifers: SEPM Concepts in Hydrogeology and Environmental Geology 1, p. 85-90.

Galloway, W. E., and D. K. Hobday, 2012, Terrigenous clastic depositional systems: applications to fossil fuel and groundwater resources: Berlin, Springer Science and Business Media, 491 p.

Garzanti, E., A. Resentini, G. Vezzoli, S. Andò, M. Malusà, and M. Padoan, 2012, Forward compositional modelling of Alpine orogenic sediments: Sedimentary Geology, v. 280, p. 149-164.

Ghielmi, M., M. Minervini, C. Nini, S. Rogledi, M. Rossi, and A. Vignolo, 2010, Sedimentary and tectonic evolution in the eastern Po-Plain and northern Adriatic Sea area from Messinian to Middle Pleistocene (Italy): Rendiconti Lincei, v. 21, p. 131-166.

Ghielmi, M., M. Minervini, C. Nini, S. Rogledi, and M. Rossi, 2013, Late Miocene–Middle Pleistocene sequences in the Po Plain–Northern Adriatic Sea (Italy): the stratigraphic record of modification phases affecting a complex foreland basin: Marine and Petroleum Geology, v. 42, p. 50-81.

Giambastiani, B. M. S., N. Colombani, M. Mastrocicco, and M. D. Fidelibus, 2013, Characterization of the lowland coastal aquifer of Comacchio (Ferrara, Italy): Hydrology, hydrochemistry and evolution of the system: Journal of Hydrology, v. 501, p. 35-44.

Giambastiani, B. M. S., N. Colombani, N. Greggio, M. Antonellini, and M. Mastrocicco, 2017, Coastal aquifer response to extreme storm events in Emilia-Romagna, Italy: Hydrological Processes, v. 31, p.1613-1621.

Hornung, J., and T. Aigner, 1999, Reservoir and aquifer characterization of fluvial architectural elements: Stubensandstein, Upper Triassic, southwest Germany: Sedimentary Geology, v. 129, p. 215–280.

Houston, J., 2004, High-resolution sequence stratigraphy as a tool in hydrogeological exploration in the Atacama Desert: Quarterly Journal of Engineering Geology and Hydrogeology, v. 37, p. 7-17.

Larue, D.K., and J. Hovadik, 2006, Connectivity of channelized reservoirs: a modelling approach: Petroleum Geoscience, v. 12(4), p.291-308.

Maliva, R. G., 2016, Aquifer Characterization Techniques - Schlumberger Methods in Water Resources Evaluation (Series no. 4): Switzerland, Springer International Publishing AG, 617 p.

Mastrocicco, M., B. M. S. Giambastiani, P. Severi, and N. Colombani, 2012, The importance of data acquisition techniques in saltwater intrusion monitoring: Water Resources management, v. 26, p. 2851-2866.

Mastrocicco, M., and N. Colombani, 2014, Modelling present and future Po River interactions with the alluvial aquifers (Low Po River Plain, Italy): Journal of Water and Climate Change, v. 5, p. 457-471.

Mazzini, E., P. Luciani, and G. Simoni, 2006, The 'Cavo Napoleonico' Channel: from the past to the present, hydraulic risk reduction programmes, the 10th IAEG International Congress, Nottingham, United Kingdom, 6-10 September, Paper no. 99.

Mele, M., R. Bersezio, and M. Giudici, 2012, Hydrogeophysical imaging of alluvial aquifers: electrostratigraphic units in the quaternary Po alluvial plain (Italy): International Journal of Earth Sciences, v., 101, p. 2005-2025.

Mele, M., R. Bersezio, M. Giudici, S. Inzoli, E. Cavalli, and A. Zaja, 2013, Resistivity imaging of Pleistocene alluvial aquifers in a contractional tectonic setting: A case history from the Po plain (Northern Italy): Journal of Applied Geophysics, v., 93, p. 114-126.

Mele, M., N. Ceresa, R. Bersezio, M. Giudici, S. Inzoli, and E. Cavalli, 2015, Resolving electrolayers from VES: A contribution from modeling the electrical response of a tightly constrained alluvial stratigraphy: Journal of Applied Geophysics, v. 119, p. 25-35.

Middleton, G.V., 1973, Johannes Walther's Law of the Correlation of Facies: Geological Society of America Bulletin, v. 84, p. 979-988.

Missiaen, T., J. Verhegge, K. Heirman, and P. Crombé, 2015, Potential of cone penetrating testing for mapping deeply buried palaeolandscapes in the context of archaeological surveys in polder areas: Journal of Archaeological Science, v. 55, p. 174-187.

Mitchum Jr., R. M., P. R. Vail, and S. Thompson III, 1977, The depositional sequence as a basic unit for stratigraphic analysis, *in* C.E. Payton, ed., Seismic Stratigraphy-Applications to Hydrocarbon Exploration: AAPG Memoir 26, p. 53-62.

Molinari, F. C., G. Boldrini, P. Severi, G. Dugoni, D. Rapti Caputo, G. Martinelli, 2007, Risorse idriche sotterranee della Provincia di Ferrara, *in* G. Dugoni and R. Pignone, eds., Risorse idriche sotterranee della Provincia di Ferrara, p. 7-61.

Morrison, J., M. Morkawa, M. Murphy, and P. Schulte, 2009, Water Scarcity and Climate Change: Growing Risks for Business and Investors, CERES, Boston, MA, US.

Muttoni, G., C. Carcano, E. Garzanti, M. Ghielmi, A. Piccin, R. Pini, S. Rogledi, and D. Sciunnach, 2003, Onset of major Pleistocene glaciations in the Alps: Geology, v. 31, p. 989-992.

Ori, G. G., 1993, Continental depositional systems of the Quaternary of the Po Plain (northern Italy): Sedimentary Geology, v. 83, p. 1-14.

Phillips, F. M., J. L. Wilson, and J. M. Davis, 1989, Statistical analysis of hydraulic conductivity distributions: A qualitative geological approach: Proceedings, Conference of New Field Techniques for Quantifying the Physical and Chemical Properties of Heterogeneous Aquifers: National Water Well Association, Dublin, Ohio, p. 19–31.

Pieri, M., and G. Groppi, 1981, Subsurface geological structure of the Po Plain, Italy, *in* M. Pieri and G. Groppi, eds., Progetto Finalizzato Geodinamica 414, C.N.R, Roma, p. 1-23.

Ponti, D. J., K. D. Ehman, B .D. Edwards, J. C. Tinsley, T. Hildenbrand, J. W. Hillhouse, R. T. Hanson, K. McDougall, C. Powell, E. Wan, M. Land, S. Mahan, and A. M. Sarna-Wojcicki, 2007, A 3-dimensional model of water-bearing sequences in the Dominguez Gap Region, Long Beach, California: U.S. Geological Survey Open-File Report 2007-1013, 39 p.

Posamentier, H. W., G. P. Allen, D. P. James, and M. Tesson, 1992, Forced regressions in a sequence stratigraphic framework: concepts, examples and sequence stratigraphic significance. AAPG Bulletin, v. 76, p. 1687-1709.

Reading, H. G., 1978, Sedimentary Environments and Facies (First Edition): Oxford, Blackwell Scientific Publications, 615 p.

Reading, H. G., 2009, Sedimentary environments: processes, facies and stratigraphy: Oxford, Blackwell Scientific Publications, 704 p.

Regione Emilia-Romagna, and ENI-AGIP, 1998, Riserve idriche sotterranee della Regione Emilia-Romagna: Firenze, S.EL.CA. s.r.l., 120 p.

Regione Lombardia, and E.N.I. Divisione A.G.I.P., 2002, Geologia degli acquiferi Padani della Regione Lombardia: Firenze, S.EL.CA. s.r.l., 130 p.

Robertson, P. K., and R. G. Campanella, 1983, Interpretation of Cone Penetration Tests: Sands: Canadian Geotechnical Journal, v. 20, p. 719-733.

Robertson, P. K., 1986, In-Situ Testing and Its Application to Foundation Engineering: Canadian Geotechnical Journal, v. 23, p. 573-594.

Robertson, P. K. 1989, Soil classification using the cone penetration test: Canadian Geotechnical Journal, v. 27, p. 151-158.

Robertson, P. K., 2010, Soil behavior type from the CPT: an update, in 2nd International Symposium on Cone Penetration Testing, Huntington Beach, CA, USA, p. 9-11.

Rossi, M., M. Minervini, M. Ghielmi, and S. Rogledi, 2015, Messinian and Pliocene erosional surfaces in the Po Plain-Adriatic Basin: Insights from allostratigraphy and sequence stratigraphy in assessing play concepts related to accommodation and gateway turnarounds in tectonically active margins: Marine and Petroleum Geology, v. 66, p.192-216.

Scardia, G., G. Muttoni, and D. Sciunnach, 2006, Subsurface magnetostratigraphy of Pleistocene sediments from the Po Plain (Italy): Constraints on rates of sedimentation and rock uplift: Geological Society of America Bulletin, v. 118, p.1299-1312.

Scardia, G., R. De Franco, G. Muttoni, S. Rogledi, G. Caielli, C. Carcano, D. Sciunnach, and A. Piccin, 2012, Stratigraphic evidence of a Middle Pleistocene climate-driven flexural uplift in the Alps: Tectonics, 31, TC6004, doi: 10.1029 /2012TC003108.

Scharling, P. B., E. S. Rasmussen, T. O. Sonnenborg, P. Engesgaard, and K. Hinsby, 2009, Three-dimensional regional-scale hydrostratigraphic modeling based on sequence stratigraphic methods: a case study of the Miocene succession of Denmark: Hydrogeology Journal, v. 17, p. 1913-1933.

Schmertmann, J. H., 1969, Dutch friction-cone penetrometer exploration of a research area at Field 5, Eglin Air Force Base, Florida. U.S. Army Eng. Waterways Exp. Stat., Vicksburg, Miss., Contract Rep. S-69-4.

Styllas, M., 2014, A simple approach for defining Holocene sequence stratigraphy using borehole and cone penetration test data: Sedimentology, v. 61, p. 444-460.

Vail, P. R., R. H., Mitchum, Jr., and S. Thompson III, 1977a, Seismic stratigraphy and global changes in sea level, Part 3: Relative changes in sea level from coastal onlap, *in* C. E. Payton, ed., Seismic Stratigraphy-Applications to Hydrocarbon Exploration: AAPG Memoir 26, p. 63-81.

Vail, P. R., R. M. Mitchum Jr., and S. Thompson III, 1977b, Seismic stratigraphy and global changes of sea level, part 4: Global cycles of relative changes of sea level, *in* C. E. Payton, ed., Seismic Stratigraphy-Applications to Hydrocarbon Exploration: AAPG Memoir 26, p. 83-97.

Van Wagoner, J.C., H. W. Posamentier, R. M. Mitchum, P. R. Vail, J. F. Sarg, T. S. Loutit, and J. Hardenbol, 1988, An overview of the fundamentals of sequence stratigraphy and key definitions, *in* C. K. Wilgus, B. S. Hastings, C. G. St. C. Kendall, H. W. Posamentier, C. A. Ross and J. C. Van Wagoner, eds., Sea-Level Changes: An Integrated Approach: SEPM Special Publication 42, p. 39-45.

Van Wagoner, J. C., R. M. Mitchum, K. M. Campion, and V. D. Rahmanian, 1990, Siliciclastic sequence stratigraphy in well logs, cores and outcrops: Concepts for high resolution correlations of time and facies: Tulsa, OK, AAPG Methods in Exploration Series 7, 55 p.

Velasco, V., P. Cabello López, E. Vázquez-Suñé, M. López Blanco, E. Ramos Guerrero, and I. Tubau, 2012, A sequence stratigraphic based geological model for constraining hydrogeological modeling in the urbanized area of the Quaternary Besòs delta (NW Mediterranean coast, Spain): Geologica Acta, v. 10, p. 373-393.

Vörösmarty, C.J., P. Green, J. Salisbury, and R.B. Lammers, 2000, Global Water Resources: Vulnerability from Climate Change and Population Growth: Science, v. 289, p. 284-288, doi: 10.1126/science.289.5477.284.

Walker, R. G., 1984, General introduction: facies, facies sequences and facies models, *in* R. G. Walker, ed., Facies Models, second edition: Geological Society of Canada, Geoscience Canada, Reprint Series 1, p. 1-9.

Walther, J., 1894, Einleitung in die Geologie als historiche Wissenschaft: Jena, Verlag von Gustav Fisher, v. 3, p. 987–993.

Weissmann, G. S., and G. E. Fogg, 1999, Multi-scale alluvial fan heterogeneity modeled with transition probability geostatistics in a sequence stratigraphic framework: Journal of Hydrology, v. 226, p. 48-65.

Willis, B.J., R. Sech, T. Sun, M. Pyrcz, and S. Connell, 2015, Fluvial Channel Belt Reservoirs, Search and Discovery Article #41671, AAPG Annual Convention and Exhibition, Denver, Colorado, 19 p.

Zappa, G., R. Bersezio, F. Felletti, and M. Giudici, 2006, Modeling heterogeneity of gravel-sand, braided stream, alluvial aquifers at the facies scale: Journal of Hydrology, v. 325, p.134-153.

FIGURE CAPTIONS

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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