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A sequence stratigraphic based geological model for constraining hydrogeological modeling in the urbanized area of the Quaternary Besòs delta (NW Mediterranean coast, Spain)

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ABSTRACT

The Quaternary Besòs delta is located on the Mediterranean coast in NE Spain. The Besòs Delta Complex includes 3 aquifers constituted by 3 sandy and gravelly bodies, separated by lutitic units. These aquifers supply water for domestic and industrial use in this area. Management of groundwater has been problematic in the Besòs delta since the 1960s, and continues to pose major problems for subsurface engineering works in this highly urbanized region. This study seeks to demonstrate the advantages of detailed geological characterization and modeling for designing and constructing a hydrogeological model.

Available information of the subsurface was compiled, integrated and homogenized in a geospatial database. The interpretation of these data enabled us to delimit geological units by means of a sequence stratigraphic subdivision. A three-dimensional facies belt-based model of the Besòs delta was built on the basis of this geological characterization. This model was used to constrain the distribution of hydraulic parameters and thus to obtain a consistent hydrogeological model of the delta, which was calibrated by data of water management and production over the last hundred years. The resulting hydrogeological model yielded new insights into water front displacements in the aquifer during the time-span considered, improving predictions in an attempt to optimize aquifer management.

KEYWORDS **Groundwater. Delta. Sequence stratigraphy. Geological model. Hydrogeological model.**

INTRODUCTION

An adequate management of the groundwater resources under metropolitan areas is becoming increasingly important in scientific, economic, social, legal and political terms (Vázquez-Suñè, 2003; Kulabako *et al.*, 2007). In numerous cases, human settlements are situated directly over sedimentary aquifers, the groundwater of which is used for industry and domestic consumption. In addition, the presence of water stored in the subsurface poses risks for civil engineering works (Bonomi and Cavallin, 1997; Vázquez-Suñé *et al.*, 2005). In such scenarios, hydrogeological models that describe and predict flow and transport in the aquifer are of great benefit to an effective management of the subsurface (Pokrajac, 1999, Vázquez-Suñé *et al.*, 2006, Carneiro and Carvallo, 2010).

The complex nature of the process that controls the sedimentary media often produces a highly heterogeneous distribution of hydrogeological parameters in aquifers. In this regard, some authors (Huggenberger and Aigner, 1999; Klingbeil *et al.*, 1999; Heinz *et al.*, 2003; Sharpe *et al.*, 2003; Ezzy *et al.*, 2006), have highlighted the importance of constraining the models of flow and transport of solutes to the sedimentological heterogeneities of the aquifer. Nevertheless, defining the geological heterogeneities that control flow behaviour in sedimentary aquifers and especially, in those located under urbanized areas, is not easy. Outcrops, where they exist, are very limited and data are sparse and are derived from diverse sources, making a suitable integration and management difficult (Velasco *et al.*, 2012).

During the last decades, advances in hydrocarbon exploitation and in hydrogeology have gone hand in hand with the development and implementation of new technologies. In this regard, the development of three-dimensional models of subsurface heterogeneity has proved to be an efficient tool for the management of reservoirs in geological scenarios that are practically inaccessible and where data are limited (Matheron *et al.*, 1987; Gundeso and Egeland, 1990; Stanley *et al.*, 1990; Weber and van Geuns, 1990; Bryant and Flint, 1993; Krum and Johnson, 1993; Deutsch and Hewett, 1996; Dubrule and Damsleth, 2001) and for the management of water resources (Ross *et al.*, 2005; Robins *et al.*, 2005; Lelliot *el al.*, 2006; Robins *et al.*, 2008). In reservoirs and aquifers in sedimentary media, the distribution of petrophysical properties that control flow is closely linked to the distribution of depositional facies. Thus, a general 3D workflow modeling of sedimentary reservoirs and aquifers involves the modeling of facies distribution at an early stage to constrain flow models. Facies models are based on the depositional model for the reservoir or aquifer and describe the sedimentary heterogeneity at multiple scales. This is a critical point in the modeling process as flow predictions are highly dependent on facies heterogeneity (Falivene *et al.*, 2006; Howell *et al.*, 2008; Cabello *et al.*, 2010).

This workflow modeling is of paramount importance to an effective management of the aquifers of highly urbanized areas in Quaternary deltas since such formations usually act as aquifers owing to their geological (*i.e.* sedimentological, petrophysical and geomorphological) characteristics (Gámez *et al.*, 2009). An example of aquifers situated under large urbanized areas is found in two deltaic formations located in the metropolitan area of Barcelona, on the Mediterranean coast in NE Spain. This very densely populated area is located on the Llobregat and the Besòs Holocene deltas (Fig. 1). This urban region, with more than 2 million inhabitants, has an active underground infrastructure, which is threatened by the presence of water in the upper meters of the two deltaic aquifers. In addition, the aquifers in the Llobregat and the Besòs deltas have been used as a water supply for domestic and industrial purposes in the last decades, which pose a serious threat to the quantity and quality of groundwater resources. Finally, given the possible continuity of the aquifers seawards and the possible connection to the sea, a sound knowledge of geology and hydrogeology both onshore and offshore is necessary to forestall marine intrusion (Abarca *et al.*, 2006; Gámez, 2007). The need to understand aquifer behaviour for an effective management has prompted the scientific community to study the geological and hydrogeological characteristics of both deltas (Marqués, 1974, 1984; Manzano, 1986; Vázquez-Suñé *et al.*, 2005; Lafuerza *et al.*, 2005; Gámez, 2007; Gámez *et al.*, 2009; Riba and Colombo, 2009). As regards the Besòs delta, a number of hydrogeological studies have been carried out during the last century. These works include Moragas (1896), Rubio and Kinderlán (1909), the hydrogeological synthesis study carried out by the Ministry of Public Works of Spain together with the Hydrographic Confederation of Eastern Pyrenees (MOP, 1966) in addition to more recent studies of Nilsson *et al.* (2002) and Ondiviela *et al.* (2005). Nevertheless, given the implications for human activity, much more research is needed to improve our understanding of deltas and the management of their aquifers.

The present paper seeks to upgrade hydrogeological modeling in deltaic depositional systems by focusing on the benefits obtained from modeling detailed subsurface geological heterogeneities. The Besòs delta was chosen as the example for this purpose.

The workflow modeling and results in this paper are presented as follows: i) a summary of the database used for the characterization and modeling of the Besòs delta; ii) the integration and synthesis of these data that enabled us to define facies association and sequence stratigraphic arrangement of the sedimentary record onshore and offshore; iii) a three-dimensional model reproducing distribution of facies associations in the Besòs delta, based on geological characterization (*i.e.,* facies belt and stratigraphic organization) and iv) a consistent hydrogeological model constructed on the basis of the three-dimensional geological model. The hydrogeological model was calibrated by historical data of water management and production of the last century to constrain and revise parameters used in the modeling process.

GENERAL SETTING

Besòs delta complex

The Besòs delta is located on the Mediterranean coast in the NE of the Iberian Peninsula (Fig. 1). It is an asymmetric, small delta that occupies an area of 17.4km^2 (Riba and Colombo, 2009). The Besòs delta is limited by the Littoral Ranges to the north, and by the Barcelona Coastal Plain to the west, which separates the Besòs delta from the neighbouring Llobregat delta (Figs. 1, 2). It is a Holocene depositional system that was also active during the Pleistocene. The delta is being constituted by sediments supplied by the Besòs River and their tributaries. The accumulated watercourse length of these rivers is about 530km and their drainage area is approximately 1038km^2 (Devesa *et al.*, 2004). The present day Besòs River displays a very low sinuosity in its lower course and has been subjected to growing pressure from anthropic activities. The irregular hydrology of the Besòs River is characterized by an alternation between long periods of drought and catastrophic flows (Riba and Colombo, 2009). The upper Besòs delta plain slope is relatively high, about 0.2º (0.35% after Sanz, 1988) and the ratio of the submerged deltaic area to the

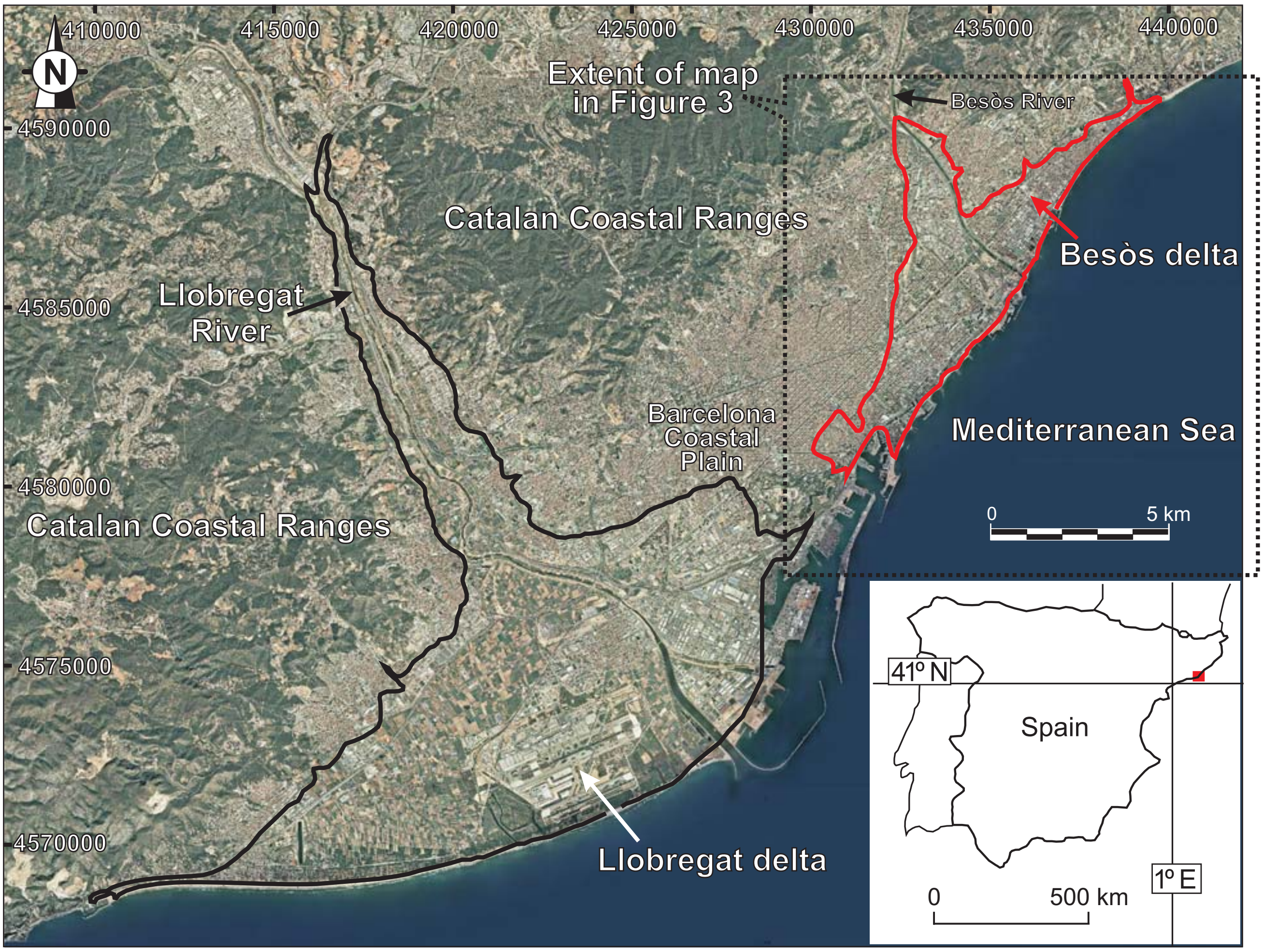

FIGURE 1 | Orthophotograph of the northeastern Mediterranean coast of Spain covering the extent of the Besòs and Llobregat emerged deltas (see red point in lower right inset for general location). Both deltas are separated by the Barcelona Coastal Plain, and are bounded by the Catalan Coastal Ranges to the north (see the Geological map of this zone in Fig. 2). Note the intense urbanization of this region, hindering outcrop existence. Coordinates are in Universal Transverse Mercator (UTM), Zone 31.

emerged deltaic area is below 2 (Serra *et al.*, 1985). The Besòs delta can be considered as an encased delta complex dominated by waves and longshore drift with coalescing minor alluvial fans derived from both margins. The Quaternary succession of the Besòs delta, which reaches a maximum thickness of 53m onshore and approximately 50m offshore (at 5km from the coastline), rests unconformably on a paleorelief (paleovalley) over a substratum formed by Paleozoic and Cenozoic rocks (Fig. 2). The Paleozoic lithologies are mainly slates and granites. The Cenozoic units are made up of Miocene matrix-rich gravels and sandstones, and Pliocene grey massive marls. As in the case of the neighbouring Llobregat delta (Gámez *et al.*, 2009), the Quaternary sedimentation of the Besòs delta was mainly controlled by glacio-eustatic sea-level changes and fault activity (Riba and Colombo, 2009).

Dataset

The study area covers the whole emerged portion of the delta in addition to the submerged part 5km offshore. The intrinsic geological complexity of the subsurface in the study area in addition to the progressive and massive urbanization that accelerated in the 1960s necessitated the compilation of geological information from a wide variety of sources (*i.e.* geological maps, geotechnical and hydrogeological perforations, etc.) both public and private. This dataset comprises: 372 boreholes of diverse origin (Fig. 3, 4); digital terrain models from the Institut Cartogràfic de Catalunya (ICC), 30x30m of resolution; a geological map of the Besòs delta and adjacent zones at 1:50,000 scale from the Instituto Geológico y Minero de España (IGME) (Alonso *et al.*, 1977), and the Institut Geològic de Catalunya (IGC) (IGC-

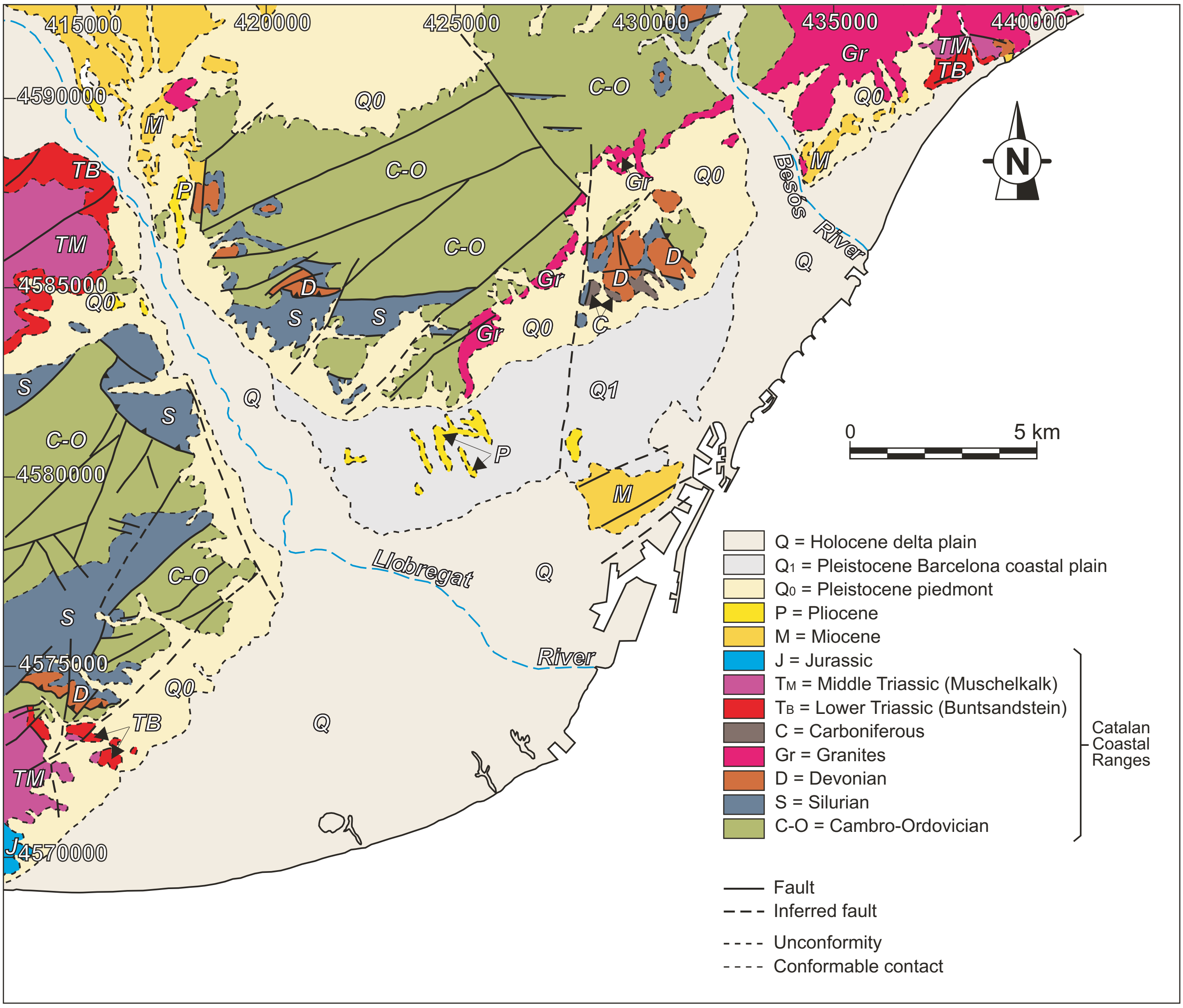

FIGURE 2 | Geological map of the Besòs and Llobregat deltas, and adjacent zones (see the corresponding orthophotograph with the extent of the emerged deltas in Fig. 1).

IGME, 2005); a geotechnical map of Barcelona at 1:25,000 (ICC, 2000); two seismic profiles from the IGME produced in 1989 (Medialdea *et al.*, 1989) (see location in Fig. 3); and a compilation of bibliographic studies comprising references dating back more than a hundred years (Llobet and Vallllosera, 1838; Cerdà, 1855; García Faria, 1891; Moragas, 1896; Almera, 1894; Almera and Brossa, 1900; Rubio and Kindelán, 1909; Solé i Sabarís, 1963; Garau, 1983; Sanz, 1988; UPC *et al.*, 1997; Montes and Vàzquez-Suñé, 2005; Simó *et al.*, 2005; Adif, 2007; Gámez, 2007; Liquete et al., 2007; Martí *et al.*, 2008; Gámez *et al.*, 2009; Riba and Colombo, 2009). Additionally, extra fieldwork and aerial photographs interpretation of the Besòs delta were carried out for the elaboration of this work. The information was introduced into a geospatial database that integrated all the available data into a coherent and logical structure that enabled us to define a conceptual depositional model of the Besòs Delta on the basis of sequence stratigraphic analysis. The structure of this database also allows us to store several interpretations and models derived from the data (Velasco et al., 2012).

FACIES AND SEQUENCE STRATIGRAPHIC ANALYSIS

Sedimentary facies belt

In the Besòs Delta, the whole range of deltaic depositional environments (from continental to marine) was identified. In addition, several facies associations were defined within each depositional environment in accordance with the grain size distribution and sedimentary features such as fauna, roundness, sorting, etc:

Continental (subaerial)

i) Proximal alluvial fan

This facies association consists of deposits of heterometric gravels interbedded with sands and red-yellow muds. It is restricted to the areas where the Besòs Delta Complex is closer to the surrounding reliefs (*i.e.*, the Littoral Coastal Ranges and the Barcelona Coastal Plain; Figs. 1, 2) and represents small-scale alluvial fan and screes derived from these reliefs.

ii) Fluvial Channel

This facies association consists of poorly sorted gravels with occasionally sandy matrix with some lenses of organic matter. The pebbles are well to poorly rounded, heterometric and polymictic. These deposits are capped by or are intercalated with the floodplain facies. This facies association is interpreted as deposits from fluvial channels and ephemeral fluvial courses. It commonly has great lateral continuity and may fill abandoned paleochannels.

iii) Floodplain facies

This sedimentary facies association is composed of continental red and yellow clays and silt intercalated with coarser-grained deposits. It is interpreted as the distal alluvial fan and river floodplain deposition during flooding events. It laterally grades to a proximal alluvial fan towards the margins of the deltaic complex and it is commonly intercalated with fluvial channel deposits. It grades from distal to coastal facies.

Transitional

Within this sedimentary depositional environment, two facies associations, which constitute the transgressive delta front and the regressive delta front of the deltaic system, were interpreted.

i) Transgressive delta front

This facies association is composed of a fining and deepening- upward succession of gravels (well rounded to angular pebbles) and sand with abundant marine fauna. It is interpreted as a reworking of alluvial and fluvial deposits by marine processes and is located on top of fluvial channels. The transgressive delta front is capped by prodelta clay and silts.

ii) Regressive delta front

This facies association consists of coarsening-upwards sandy units grading into gravels with abundant micaceous

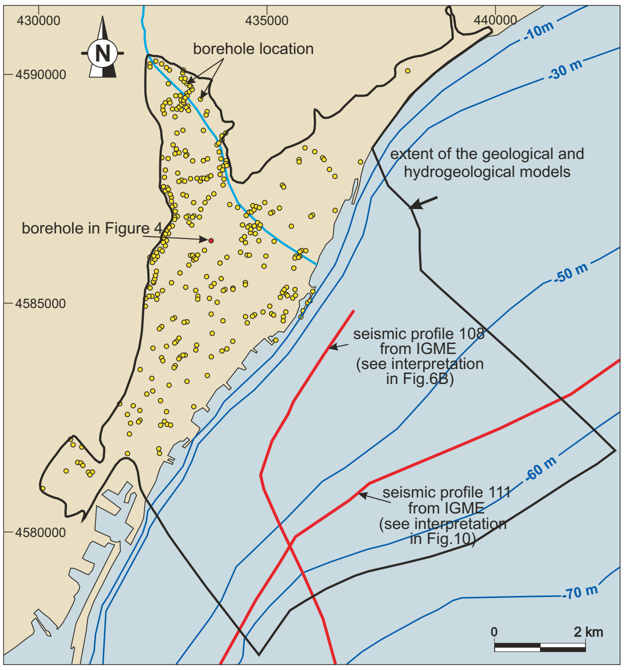

FIGURE 3 | Schematic map showing the location of the boreholes used for the stratigraphic correlation and geological modelling (see an example of a borehole interpretation in Fig. 4); the location of part of two seismic profiles, on which the stratigraphic correlation in the submarine part of the delta was based (see interpretation of seismic profile 108 and profile 111 in Fig. 6 and 10); and the extent of the geological and hydrogeological models. Note that the models presented cover the whole emerged portion of the delta (see Fig. 1), and extend five kilometres seawards from the coast including a portion of the submarine part.

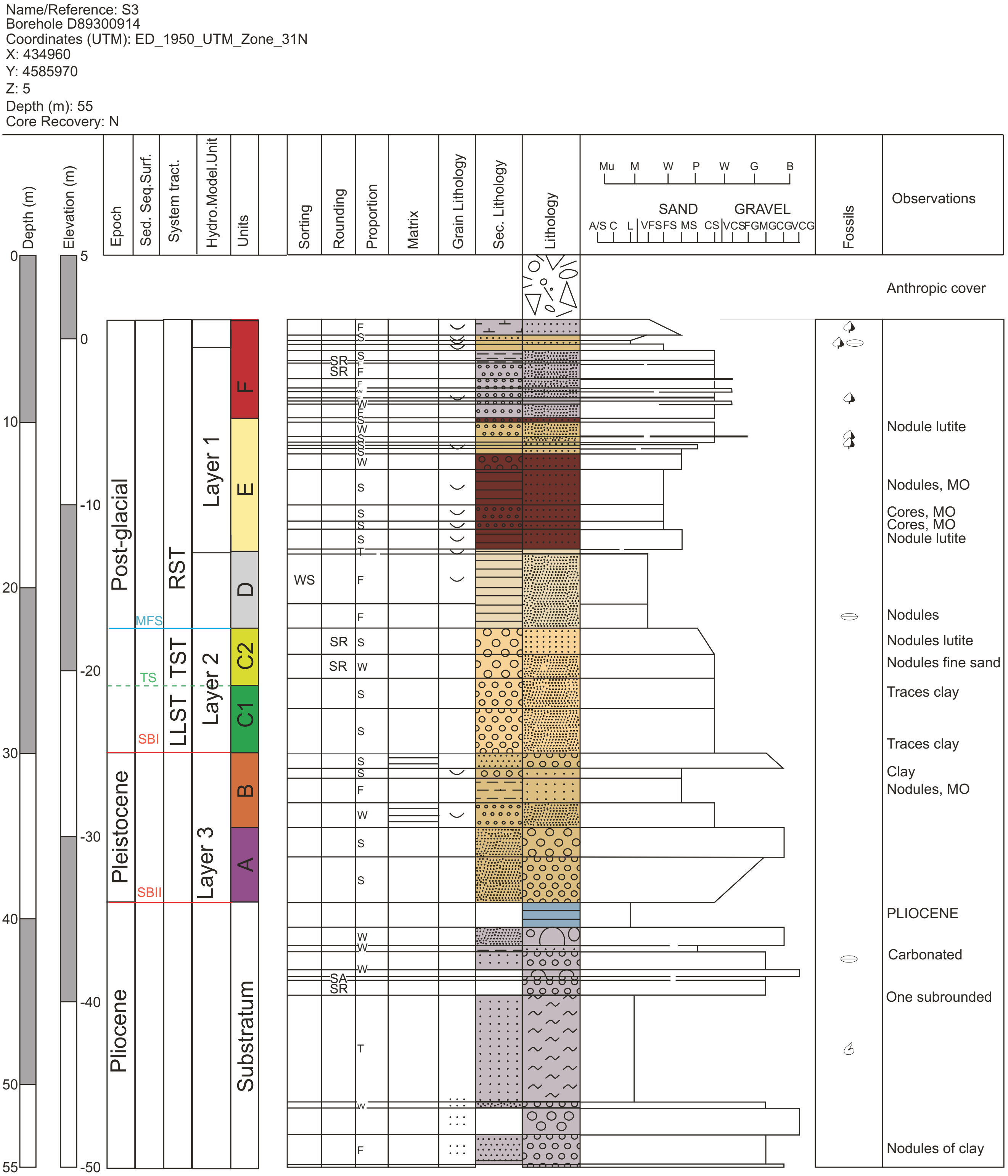

FIGURE 4 | Example of a borehole interpretation from the dataset compiled and used for the stratigraphic correlation and geological modelling. The lithology is defined by three components: Lithology (main litholgy), secondary lithology and matrix. The proportion between the secondary and the main lithology is represented by the column labelled as Proportion. The seven geological units distinguished, the stratigraphic surfaces and the system tracts, and the hydrogeological units of the model are indicated. Units A and B are included in the Pleistocene sequence, whereas units C1, C2, D, E and F correspond to the postglacial upper sequence.

minerals and some shell fragments. It is interpreted as being the product of the progradation of the Delta front. It grades to fluvial channels and to floodplain upwards and to the margin.

Marine

i) Prodelta
Within this depositional environment one facies association comprising gray clays and silts with intercalations of fine sands and sparse marine fauna were identified. This association is interpreted as the Prodelta of the deltaic complex deposited below the storm wave base. The Prodelta facies belt is located in the SE of the delta and grades to the delta front to the NW.

Sequence stratigraphic subdivision

Coastal and deltaic successions usually develop complex architectural arrangements owing to their sensitivity to relative sea-level changes. This type of complex architecture is governed by the relationship between accommodation (subsidence+eustasy) and sediment supply. Given that this case study deals with present-day and recent delta deposits, eustatic variations played an important role in their architectural development, as in other recent Mediterranean delta systems (*e.g.*, Somoza *et al.*, 1998; Montaner and Solà, 2004; Gámez *et al.*, 2009).

Because this architectural arrangement was influenced by sea level changes, a sequence stratigraphic analysis of the Besòs delta succession is necessary to differentiate a series of sequences, systems tracts and key surfaces. This differentiation is useful to correlate boreholes, to predict depositional (and granulometric) trends and to forecast the geometry of the main facies belts in order to build a robust geological model.

The estimated ages are based on the comparison with depositional architectures described in other Mediterranean delta plains and shelves (*e.g.,* Llobregat Delta, Ebro Delta) (Gámez, 2007; Gámez *et al.*, 2009).

The geological model of the Besòs delta in this study is based on a sequence stratigraphic subdivision. This subdivision resulted from the identification of key stratigraphic surfaces and the general trends (progradational-retrogradational or coarsening/fining upwards) observed in the marine and transitional sediments in the boreholes.

After the identification of the key surfaces and the different system tracts within the boreholes, these sequence stratigraphic units and key surfaces were correlated along several correlation panels covering the entire delta complex.

The delta was subdivided into two sequences, with thicknesses in the order of tens of meters, bounded at the base by widespread erosional surfaces (even paleoreliefs; Fig. 5). These erosional surfaces represent periods of subaerial erosion, probably related to relative sea-level falls associated with glacio-eustatic sea-level variations during the Quaternary. An accurate study of the coastal and marine facies succession is necessary to establish a reliable sequence stratigraphic subdivision. In this case study, the lower stratigraphic unit between two erosional surfaces is mainly constituted by continental sediments (Fluvial facies association and floodplain facies association). Owing to the lack of information about the sequential trends of time-equivalent marine and transitional deposits, an internal sequence stratigraphic subdivision in systems tracts was not developed.

The uppermost sequence embraces the whole range of facies belts (from subaerial to submarine) and a series of key surfaces and systems tracts have been defined. This sequence consists of: i) a lower late lowstand systems tract (Posamentier and Allen, 1999), ii) a transgressive systems tract (Van Wagoner *et al.*, 1988), and iii) an upper regressive systems tract (Embry and Johannessen, 1992).

The late lowstand systems tract is identified by fluvial channels resting above the erosive surface (*i.e.,* sequence boundary; Fig. 5). These channels were deposited during an initial relative sea-level rise after a sea-level fall, filling the erosive reliefs developed during the sea-level fall.

The transgressive systems tract is constituted by reworked channel facies association (Transgressive delta front). The basal surface is a transgressive surface, interpreted as a wave-ravinement surface, and is characterized by a gravelly lag derived from the reworking of late lowstand systems tract fluvial channel deposits during transgression. The top surface is a maximum flooding surface that in well logs was traced directly over a lithological change, recording an abrupt deepening of the water lamina reflected in prodeltaic sediments. The maximum flooding surface marks the change from fining/deepening-upwards to coarsening/shallowing-upwards vertical trends and also the change from retrogradational to a progradational arrangement in the delta front facies belt.

The regressive systems tract shows coarsening and shallowing upwards trends (from prodelta marly clays and silts to delta front sands and gravels) and displays a progradational stacking pattern.

According to Garriga (2007), the arrangement of the Besòs delta is similar to the one described by Gámez *et al.* (2005) for the neighboring Llobregat delta. It is reasonable, therefore, to assume that the sequential arrangement in the Besòs delta was controlled by absolute sea-level changes

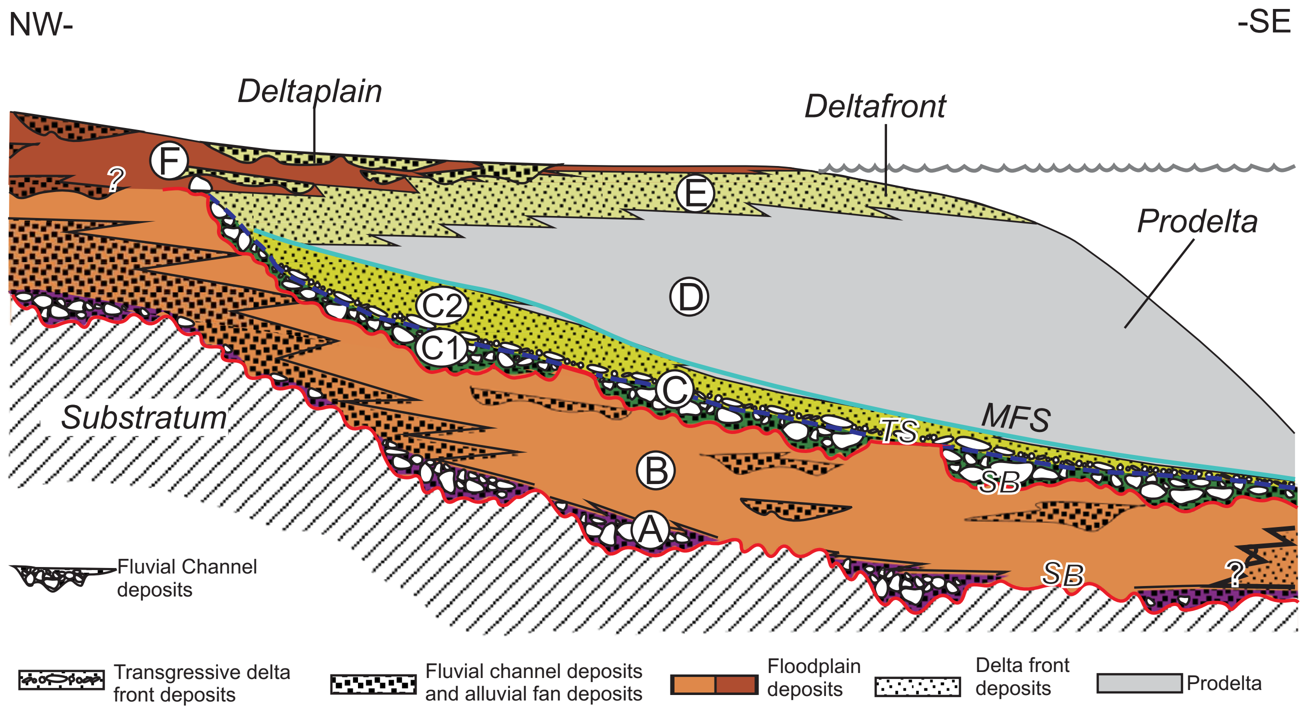

FIGURE 5 | Synthetic cross-section showing the stratigraphic organization of the Besòs delta. Two widespread erosional surfaces, *i.e.* sequence boundaries (SB), subdivide the delta succession into two sequences: the lower Pleistocene sequence and the upper Postglacial sequence. In the Postglacial sequence, three systems tracts are distinguished: a lower late lowstand systems tract, in between the sequence boundary and a transgressive surface (TS); a transgressive systems tract, bounded by the transgressive surface and a maximum flooding surface (MFS); and an upper regressive systems tract above the maximum flooding surface. This sequence stratigraphic subdivision was correlated seawards with previous descriptions and interpretations of the submerged delta (see seismic profile interpretation in Fig. 6). The sequence stratigraphic surfaces and additional lithostratigraphic boundaries allowed to distinguish seven geological units (A to F), which present different sedimentological, and thus petrophysical and hydraulic properties (see Table 1 and 2 for more details).

occurring during the Quaternary as described by Gámez *et al*. (2005, 2009) and Gámez (2007) for the Llobregat Delta. Thus, the development of the defined systems tracts and sequences was controlled mainly by absolute sea level variations and sediment supply. Consequently, the uppermost sequence, Postglacial in age, records the decelerating sea-level rise after the last glacioeustatic minimum. The lowermost sequence, which is of Pleistocene age, probably records the last complete glacioeustatic cycle.

The correlation of the proposed stratigraphic subdivision with previous descriptions (Medialdea et al., 1989; Gámez, 2007) of the submerged delta based on seismic profile interpretations and borehole correlations provides an overall framework for the quaternary stratigraphic architecture of the continental margins.

This correlation enables us to establish the following equivalents (see Fig. 6C): the regressive systems tract and the transgressive systems tract of the Postglacial sequence were found to be equivalent to unit Q4 proposed by IGME (Medialdea *et al*., 1989). The Postglacial late lowstand systems tract and its basal unconformity correspond to the late lowstand systems tract of unit Q3 and to the forced regression systems tract of unit Q2. The Pleistocene sequence is equivalent to the highstand and the transgressive systems tracts of units Q2 and Q1.

GEOLOGICAL AND HYDROGEOLOGICAL MODEL

Geological model

The Besòs models presented in this paper are concerned with the emerged part of the delta in addition to 5km of the submerged part (Fig. 3). Stratigraphically, the model includes the entire delta succession ranging from Pleistocene deposits at the base to the Present top surface with stratigraphic thicknesses between 7.5 and 53.5m onshore and about 50m (5km from the shoreline) offshore.

The analysis of the stratigraphic organization and facies belt arrangement of the delta (see previous Section sedimentary facies belt and sequence stratigraphic subdivision) constituted the basis for the geological model.

A software platform developed by the Hydrogeology Group (GHC; UPC-CSIC) (Velasco *et al.*, 2012) was used for these tasks. This software was developed in the ArcMap software package and contains a set of tools that enables us to interpret borehole information, create geospatial profiles and to construct a 3D geological model.

Seven stratigraphic surfaces were identified in the boreholes in order to establish the stratigraphic framework. Four of them were derived from the sequence stratigraphic subdivision (*i.e.,* the two sequence boundaries, and the transgressive surface and the maximum flooding surface of the Holocene sequence) and are identifiable by abrupt facies contrasts (Fig. 5). Three additional surfaces were defined to constrain the geometry of the significant and correlatable lithostratigraphic units. These were as follows: the top of the discontinuous basal Pleistocene fluvial channel-fill, the base of the regressive delta front in the Holocene regressive systems tract, which separates delta front sands from clays and silts of the prodelta and the limit between fine-grained delta plain deposits and coarse-grained sediments made up of sands and gravels from the delta front and the fill of the main channels in the delta plain of the upper sequence (Fig. 5). These surfaces were correlated between the boreholes in the emerged part of the delta, and thirteen cross-sections were generated (see Fig. 7). The result of this subdivision enabled us to differentiate between seven units (A to F; Figs. 4, 5, 7), which are of sequential significance. The interpolation of the mapped traces from the thirteen cross-sections in non-sampled areas allowed us to obtain a three-dimensional reconstruction of the Besòs delta (Fig. 8). The main features of the units distinguished in this model (*i.e.* lithology and depositional environment) are summarized in Table 1 and their extent in the emerged Delta Complex is represented in Figure 9.

After the construction of a geological model onshore, an extension of this model offshore was needed to obtain an overall understanding of the delta. (see Figs. 6, 10).

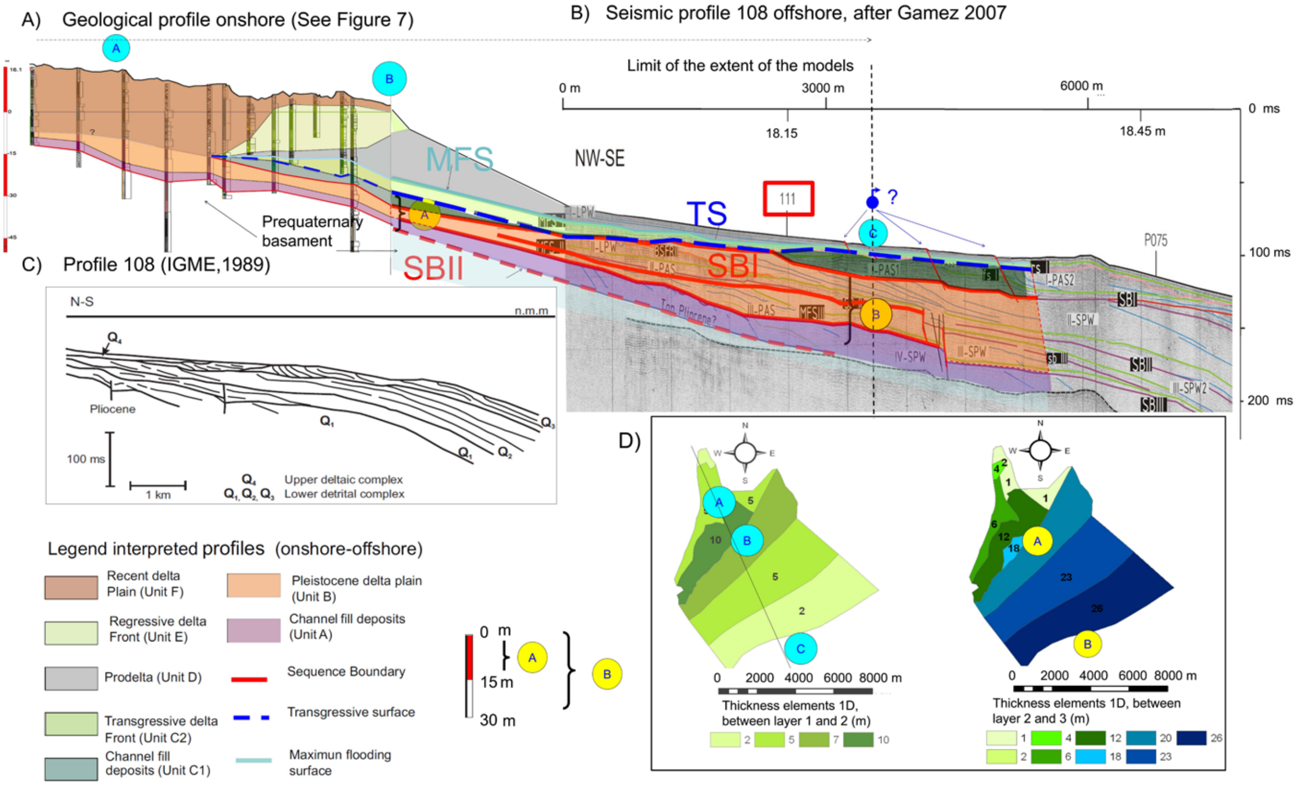

FIGURE 6 | A) and B) Correlation of a geological profile onshore A) (for further details and location of this geological profile, see Fig. 7) and the interpretation of the seismic profile number 108 of the submerged delta of Besòs after Gámez (2007); B) see location in Figure 3. The sequence stratigraphic surfaces and the different units defined can be visualized onshore in the geological profile interpreted (A) and offshore in the interpreted seismic profile. Notice that there is a vertical scale to show the thickness of the units. See also the profile 111 in Figure 10 (see location in seismic profile and in Fig. 3) and Figure 7 and sections: Facies and sequence stratigraphic analysis and Geological model. C) Interpretation of the seismic profile 108 from IGME, (Medialdea *et al.*, 1989). The Upper deltaic complex, unit Q_4, correlates with the regressive and the transgressive systems tract of the Postglacial sequence described; the lower detrital complex comprises units $Q_{3,}$ Q_2 and $Q_{1,}$ and correlates with Postglacial late lowstand systems tract, and with the Pleistocene sequence described herein. See Figures 5 and 7 and section Facies and sequence stratigraphic analysis for more details. D) Thickness maps of the aquitard's elements of the hydrogeological model. Notice that also these maps show the location of the profile onshore-offshore exposed in A and B.

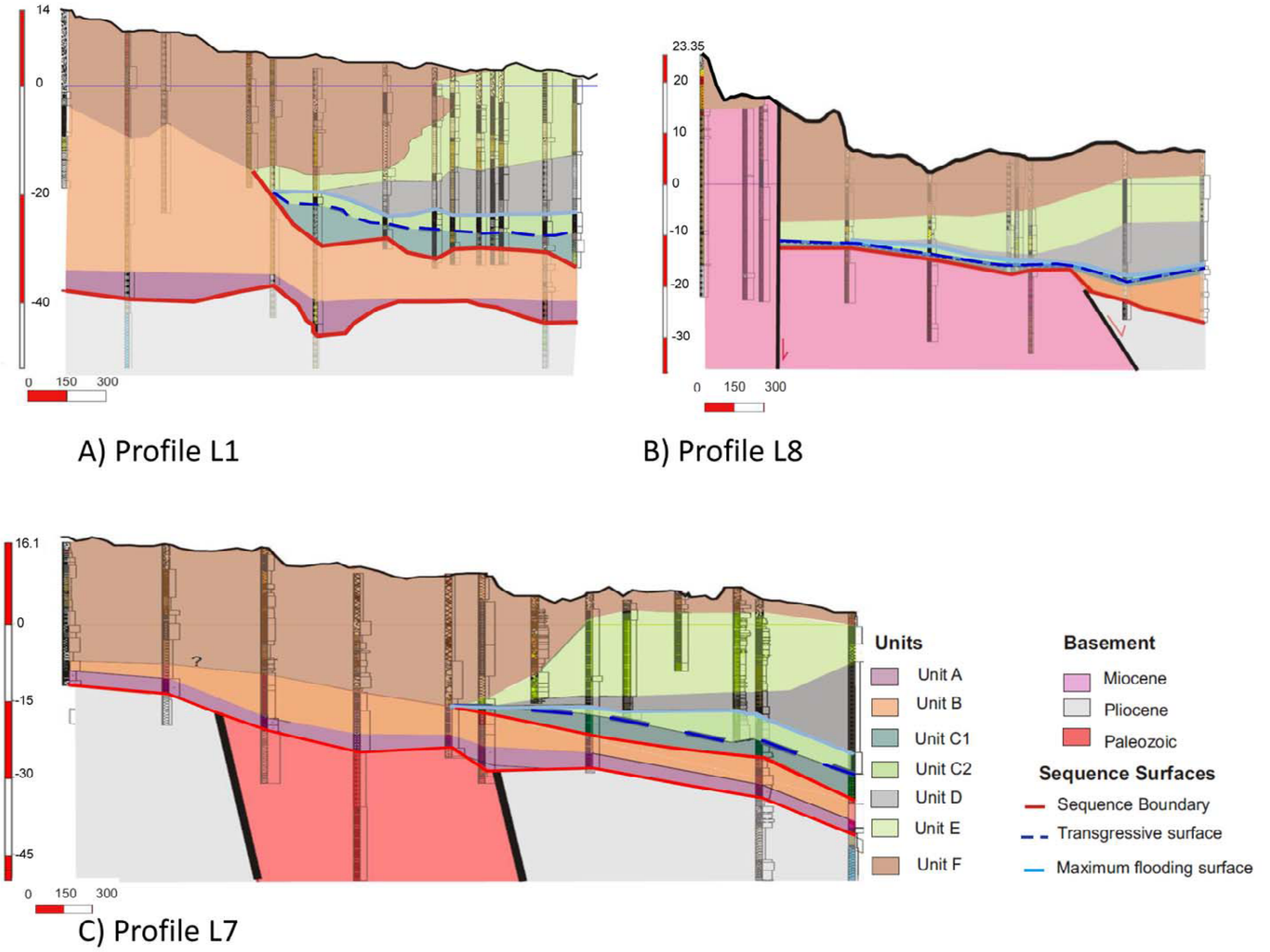

FIGURE 7 | Three cross sections perpendicular to the coast. The sequence stratigraphic surfaces and the different units can be visualized. The location is showed in Figure 8A. See section geological model for detailed description of the units and the sequence stratigraphic interpretation.

From the sequence stratigraphic-based correlation between the onshore-offshore delta (see sequence stratigraphic subdivision), a stratigraphic correlation was also performed owing to the fact that different sequences and system tracts do not develop constant lithological properties.

The progradational delta-front sand-wedge (Unit E) at the Holocene RST pinches out approximately 500m from the coastline (after Liquete *et al.*, 2007).

The prodelta muds (Unit D) belonging to the Holocene RST, thin out progressively seawards and cover most of the modelled submerged delta.

The transgressive fan delta front wedge on the TST (Unit C2) thins out seawards. It is not easy to determine its extension on the submarine delta but, the merging of the Postglacial transgressive surface with a transgressive ravinement surface (Gámez, 2007) supports the idea that some sands and gravels extend above the Transgressive Surface several kilometres offshore.

The channel fill gravels on top of the basal boundary of the Postglacial sequence (Unit C1) are difficult to follow offshore since no major channelled erosive surfaces have been distinguished in profile 108 after Gámez (2007) (see Fig. 6A, B). Time-equivalent units corresponding to these channel-fill gravels in the offshore present a wedge-shape geometry and depict seaward prograding clinoforms. Probably there was a progradational delta front building (offshore) simultaneously to the channel infill in more proximal areas (onshore). Nevertheless, this Unit is easily identified above the upper sequence boundary (SBI) in the profile 111 (see Fig. 10).

Delta plain muds in the Pleistocene Unit B were difficult to identify in the offshore domains since most of the reflectors show clinoform geometries related to coastal and submarine progradation. Thus, these delta plain sediments (Unit B) quickly pass offshore to coastal and marine facies.

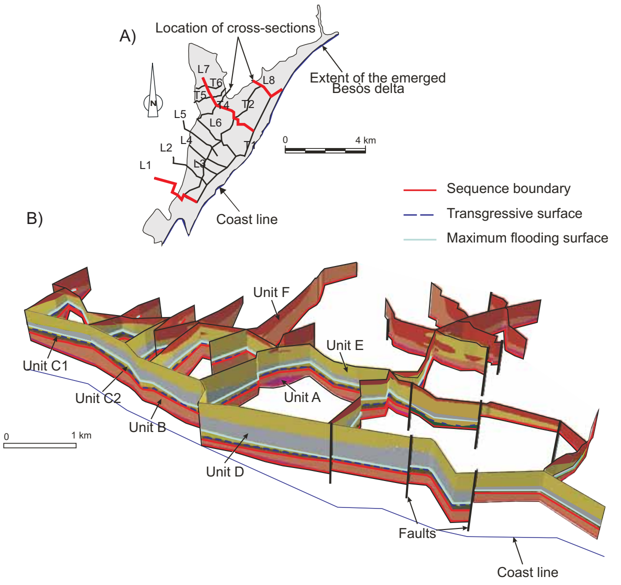

FIGURE 8 | A) Location of the cross section performed to construct this fence-diagram (notice that the location of the cross section of the Figure 7 are coloured in red), B) Geological model of the Besòs delta viewed by means of thirteen cross-sections generated, showing the geometry and continuity of the seven geological units distinguished (view is from E).This model has been performed by using a software platform developed by the Hydrogeology Group (GHS; CSIC-UPC) (for further information see Velasco et al., 2012). The sequence stratigraphic surfaces (i.e. sequence boundaries, the transgressive surface and the maximum flooding surface) are also indicated. See characteristics (i.e. lithology, depositional environment, facies association and geometry) of the geological units distinguished in Table 1.

Channel fill gravels (Unit A) are associated with the lowermost sequence boundary (SBII) and are not easy to correlate offshore from the seismic data interpreted by Gámez (2007) in the seismic profile 108. This is probably a surface where other sequence boundaries coalesce. Figure 9 shows that Unit A infills NW-SE oriented paleovalleys onshore. This was born in mind when including the NW-SE elongated gravel units corresponding to Unit A in our offshore model.

As shown in Figure 6B, a series of normal faults (some of them lystric) were observed at a distance of 5km offshore. At this point, Unit D reaches its minimum thickness and is cut by these faults, which lead us to strongly consider a connection of the main aquifer units (constituted by C1 and C2) with the sea.

THE HYDROGEOLOGICAL MODEL

Definition of the aquifers and the status of groundwater

A number of specific issues must be considered when dealing with groundwater in extensive urbanized areas such as the Besòs delta. Urbanization has a major impact on the quality and quantity of groundwater resources. The main difference between groundwater analysis in urbanized areas and groundwater analysis in natural systems lies in the evaluation of recharge since different water sources are involved in urbanized areas. In addition, groundwater can affect subsurface city infrastructures such as public transport services and conductions (Vázquez-Suñé *et al.*, 2005).

Traditionally, the aquifers of the Besòs delta were mainly exploited for industrial and domestic purposes. Until 1940, their exploitation was moderate, and was mainly concerned with watering and domestic supply. Subsequently, water extraction increased until it reached 66hm^3/yr in the late 1960s because of the growth of industrial activity (MOP, 1966; Ondiviela *et al.*, 2005). This extraction led to overexploitation of the aquifers of the area, bringing about a marked decrease in the phreatic level, which resulted in

TABLE 1 | Facies association, description, geometry and correlation with the different units defined for the geological model of the depositional environments distinguished in the Besòs Delta

Deltaic depositional environment	Facies association	Description	Geometry	Geological units of the model
Delta plain	Fluvial channel	Poorly sorted gravels, occasionally with sandy matrix and some lenses of organic matter. The pebbles are well rounded and polymictic	Concave up-shape	A , C1, and part of B and F
	Floodplain	Red and yellow clays	Large extension and lateral continuity	F, B (part of)
	Alluvial fan	Interbeded deposits of heterometric gravels and sands derived from sourronding relieve	Sheet-like shape	F, B (part of)
Delta front	Regresive Delta front	Yellow to gray coarse grained facies belt made up by sands and gravels. (from distal to proximal). Shells fragments	Dipping clinoform shape and flat bases	E
	Transgresive delta front	Gravels well rounded to angular pebbles with sand. Sparse shell fragments	Large extension and lateral continuity	C2
Prodelta	Prodelta	Grey clay and silts with intercalation of fine sand and with marine fauna	Wedge shape	D

marine intrusion (Vázquez-Suñé and Sánchez-Vila, 1999). In order to mitigate the progressive salinization of the aquifers, the possibility of recharging them with treated residual water has been considered (Custodio et al., 1976). Deterioration of the quality and quantity of water from the aquifer due to its overexploitation and due to dumping waste into the river and subsoil obliged many industries to discontinue groundwater extraction or to move outside the urban area. Since the1960s, the extraction in the Besòs delta aquifers has decreased, with an estimated figure of 20hm^3/yr. The reduction in extraction involved the recovery of the aquifers, which increased infiltrations in many underground infrastructures (Ondiviela *et al*., 2005). At present, the Catalan Water Agency (*i.e.,* ACA, Agència Catalana de l'Aigua) is developing a groundwater management programme to recover groundwater quality and quantity with the aim of guaranteeing sustainable pumping rates.

The hydrogeological model presented in this paper involved an exhaustive review of previous hydrogeological works developed in this area (*e.g.,* Moragas, 1896; Rubio and Kinderlán, 1909; MOP, 1966; Nilsson *et al*., 2002; Ondiviela *et al*., 2005; Ferrer, 2005; Tubau *et al*., 2009; De Buen, 2009). The proposed model makes use of the geological characterization of the Besòs delta and the subsequent geological model. As a result, three aquifer units and two aquitards in the Besòs delta were identified and their geometry and connection were characterized by the 3D geological model (see the geological model section and Table 2).

Aquifer units

i) Lower aquifer
It is mainly constituted by a Pleistocene fluvial channels (Unit A). These deposits rest unconformably on the top of relatively impermeable Paleozoic to Cenozoic rocks and deepen seawards. Moreover, in some parts of the Delta Complex, the fluvial channel deposits and the alluvial fan of the Pleistocene Delta Plain (Unit B) increase the thickness of this aquifer.

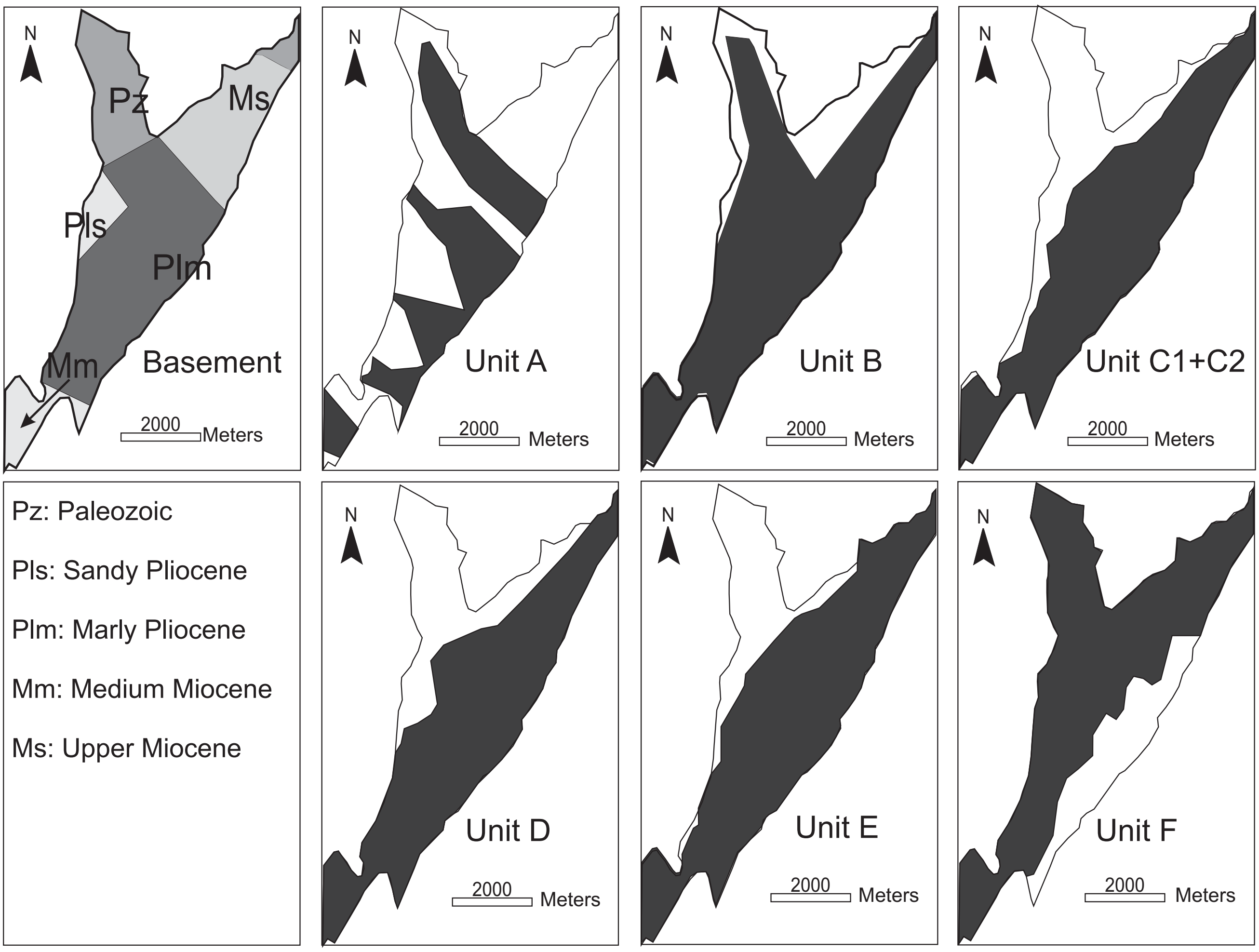

FIGURE 9 | Map showing the spatial distribution of the different units considered and of the basement.

ii) Main aquifer
This comprises units C1 and C2 and is the main aquifer of the Besòs delta. Unit C1 is constituted by a fluvial channels and Unit C2 corresponds to the aforementioned transgressive delta front facies association.

iii) Shallower aquifer
A third, shallower aquifer corresponds to Unit E, which is formed by the Holocene regressive delta front. In addition, the coarser deposits of Unit F (alluvial fans and fluvial channels) partially cover Unit E, thickening the shallower aquifer.

Aquitard units

i) Lower Aquitard:
The main aquifer is separated from the lower aquifer by a less permeable body corresponding to Unit B, which is constituted by Pleistocene delta plain sediments.

ii) Upper Aquitard:
The shallower aquifer is separated from the main aquifer by the Holocene prodeltaic Unit D, which is less permeable. Unit D peters out landwards, allowing a partial connection between the shallow and the main aquifers.

In addition to defining the aquifer and aquitard units, the conceptual hydrogeological model of the Besòs delta necessitated the determination of other input variables, such as areal recharge or groundwater extractions. In the Besòs delta, the areal recharge was estimated taking into consideration the sewage system and loss in water supply (Vázquez-Suñé *et al.*, 2005). Besides, groundwater extractions have been evaluated taking into account information from industries and water supply wells.

Hydrogeological modeling

A quasi-3D model was built to simulate groundwater flow and chloride transport in the Besòs delta aquifers. The flow and transport problem used a finite element grid of 2977 nodes and 6565 elements divided into three layers. The top layer represents the shallower aquifer, the intermediate layer the main aquifer, and the bottom layer represents the lower aquifer. In order to establish the connection between the aquifer layers, one-dimensional elements were defined between each layer. These one-dimensional elements represent the layers defined in the geological model as less permeable units D and B, and were assigned their corresponding thicknesses. The submerged portion was modeled by extending the model domain 5km seawards (Fig. 6, 8).

Variable density effects were not considered in the numerical model given that vertical fluxes can be neglected in aquifers with small thicknesses, as in the case of the Besòs delta aquifers (Abarca *et al.*, 2006). Equally, lateral variable density fluxes were also neglected in the model since their effect is considerable when the lateral slope exceeds 3% (Abarca *et al.*, 2007), which is not the case in the Besòs delta. By contrast, the significant effect of boundary heads was integrated into the model by defining seaside boundary conditions in terms of equivalent freshwater heads.

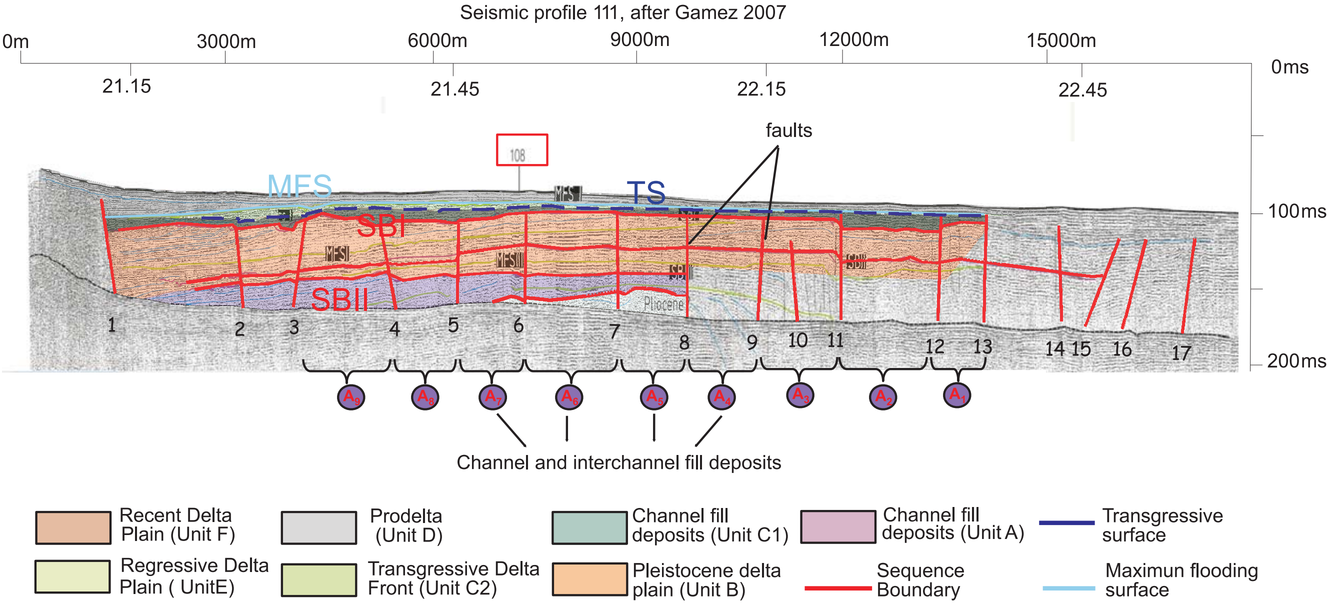

FIGURE 10 | Interpretation of the seismic profile 111 (after Gámez 2007). See Figure 3 for location. The sequence stratigraphic surfaces, the different units and the set of faults that conditioned the orientation of the interpreted interchannel and channel deposits (numbered from A1 to A9) can be visualized. As well, the interpreted interchannels and channels can be visualized in Figure 11.

TABLE 2 | Facies association, description, geometry and correlation with the different units defined for the geological model of the depositional environments distinguished in the Besòs Delta

Age	Geological units	Sedimentary environmental deposits/ Facies association	Hydrogeological units	Description Hydrogeological units
Post-glacial	F	Delta Plain (floodplain deposits)		Less permeable unit
	F	Delta Plain(fluvial channel fill deposits and alluvial deposits)	Layer 1	Shallower aquifer
	E	Regressive Delta Front		
	D	Prodelta	One-dimensional layer 1	Less permeable /aquitard
	C2	Transgressive Delta Front	Layer 2	Main Aquifer
	C1	Fluvial Channel fill deposits (Delta plain)		
Pleistocene	B	Delta Plain(floodplain deposits)	One-dimensional layer 2	Less permeable /aquitard
	B	Delta Plain (fluvial channel fill deposits)	Layer 3	Lower Aquifer
	A	Fluvial channel deposits		

Visual Transin (UPC, 2003) is a graphical user-friendly interface for TRANSIN (Medina and Carrera, 2003), which allows simulation and calibration of flow and transport parameters. This code was used for automatically calibrating the numerical model versus both head and chloride data. Three conditions must be met when calibrating the model: consistency between prior information and calibrated values; a good fit between measured and computed data in terms of both piezometric heads and chloride concentrations; and consistency between water and chloride mass balances with respect to the conceptual model and previous calculations. In the hydrogeological model of the Besòs delta, spatial discretization is refined near the main pumping areas, and the mesh is adapted to the main hydrogeological features. The average size per element is about 100m in length. The model was calibrated by using historical data of water management and production in the last hundred years. Calibration time was set from 1915 to 2006 inclusive. The calibration procedure required the prior estimation of all the model parameters, which were mainly based on data integration and geological review. For instance, 46 transmissivity zones were initially defined. The definition of these zones were conditioned to: the geometry and thickness of the different sedimentological bodies, the textural properties of each defined facies correlated with permeability values, and finally the punctual values obtained from hydraulic testing (performed for this study and derived from previous studies).

In general terms, the transmissivity values obtained by calibration satisfactorily fitted the information provided by the conceptual model. Figure 11 shows the transmissivity values calibrated for the model. Transmissivity tends to be higher in the areas of the aquifer where the grain size is coarser, and especially where the fluvial channels are presumably located.

A similar procedure of calibration was used with the remaining parameters (*i.e.,* storage coefficient, areal recharge, boundary flows and pumping rates), obtaining a satisfactory fit both in terms of heads and chloride concentrations. The calibrated model yields a reasonable fit between measured and calculated data for both chloride concentration and head (Fig. 12).

DISCUSSION

The role of sequence stratigraphy in geological and hydrogeological modeling

The geological model of the Besòs delta was developed using a sequence stratigraphic approach. Sequence stratigraphy has been used in the oil industry for decades (*e.g.,* Mitchum, 1977; Payton, 1977; Vail *et al.*, 1977; Posamentier and Vail, 1988; Van Wagoner *et al.*, 1990). This approach offers an interesting perspective on the architecture of sedimentary bodies when geological controls and processes are considered.

A number of modeling studies have highlighted the importance of a sequence stratigraphic analysis when modeling reservoir heterogeneity. Ainsworth *et al.* (1999) compared flow responses from models that used a lithostratigraphic correlation and those that employed chronostratigraphic correlation in a lacustrine delta in the Sirikit field (Thailand). The studies of Cook *et al.* (1999) and Larue and Legarre (2004) focused on a shallow marine reservoir in the Meren field (offshore Nigeria). In the former work, a sequence stratigraphic analysis was used to determine the geological framework of marine flooding surfaces and sequence boundaries on which the facies modeling was based. These authors concluded that the vertical compartmentalization in the reservoir was mainly produced at the flooding surface which separated mudstone beds from sandstone deposits. The study of Larue and Legarre (2004) revealed the differences in trapped oil distribution predict-ed by models based on a detailed sequence stratigraphic analysis and those based on a large scale analysis. A very detailed sequence stratigraphic subdivision of a transgressive-regressive sequence of an outcropping fan-delta was used by Cabello *et al.* (2010) and Cabello *et al.* (2011) as a modeling framework to reproduce the interfingering scales that controlled distribution of facies associations that may affect flow.

Owing to the parallels between sedimentary reservoirs and aquifers, the present paper makes use of sequence stratigraphy to provide new insights into the Besòs delta architecture and to derive geological and hydrogeological models. This methodology is in line with several studies of aquifers such as those by Sugarmann and Miller (1996); Pendas (2002); Houston (2004); Gámez (2007); Gámez *et al.* (2009) and Scharling et al. (2009).

There were three reasons for adopting the sequence stratigraphic approach in the Besòs delta:

Given the variety of the dataset and given the complexity and variability of facies distribution in the delta, the identification of the surfaces using sequence stratigraphy yielded a good correlation between the boreholes for the emerged part of the delta. The sequence stratigraphic subdivision was undertaken by: the identification of different depositional environments, the identification of progradational-retrogradational and coarsening or fining upwards trends and the detection of sharp erosive surfaces.

The characterization of the submerged part of the delta was not easy, given the lack of onshore-offshore geological mapping. In this regard, the methodology of sequence stratigraphic correlation offers an optimum approach since it is able to provide tools to correlate interpreted surfaces and system tracks onshore and offshore. We undertook a sequence stratigraphic correlation between the emerged delta and 5km of the submerged delta, which enabled us to obtain an overall framework for the quaternary architecture of the Besòs delta.

The sequence stratigraphic surface correlation allowed us to constrain the distribution of facies associations more reliably than using lithostratigraphic-based correlation and modeling. The resulting subdivision into seven geological units by means of sequence stratigraphic and subordinated lithostratigraphic surfaces satisfactorily represents the petrophysical properties found. This provides a more realistic assignment of the hydraulic properties for each geological body.

The deltaic nature of the stratigraphic succession enabled us to apply the sequence stratigraphic approach to

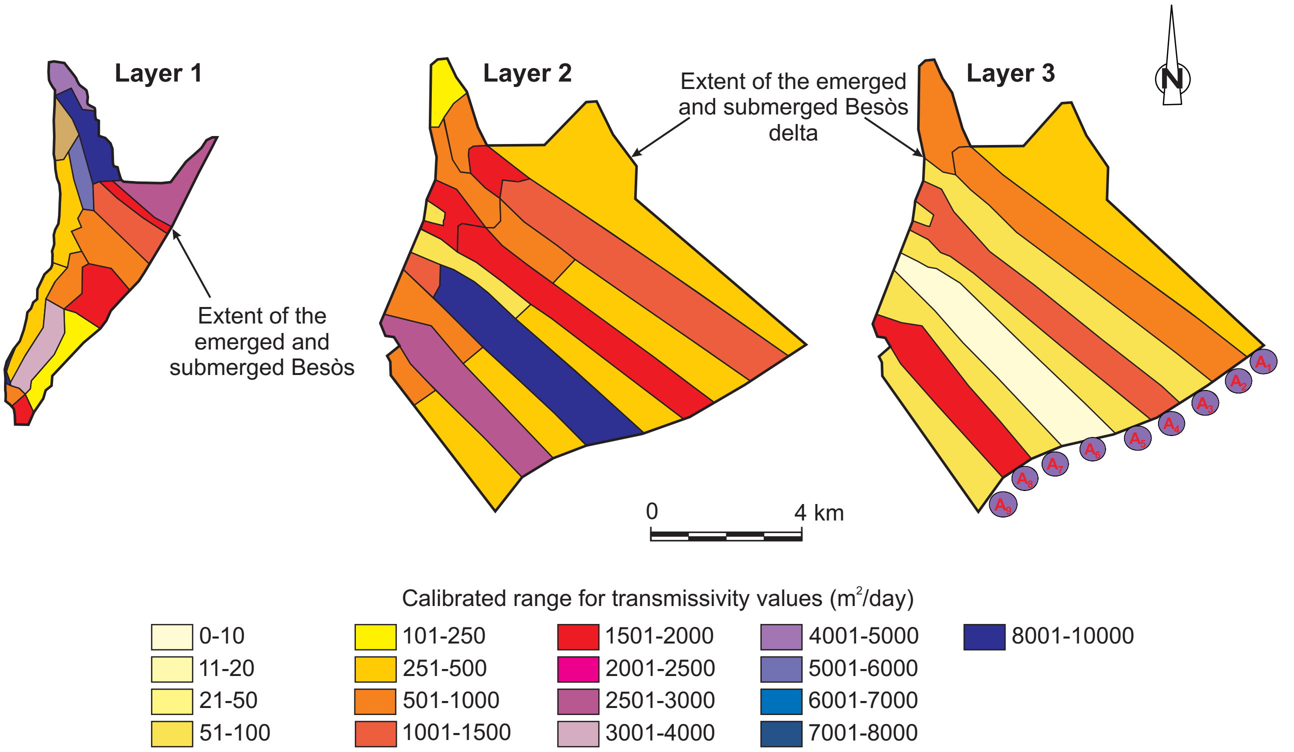

FIGURE 11 | Maps showing the transmissivity values obtained by calibration of the aquifer layers. Layer 1 corresponds to the shallower aquifer; layer 2 corresponds to the main aquifer and layer 3 is the lower aquifer (see Table 2).

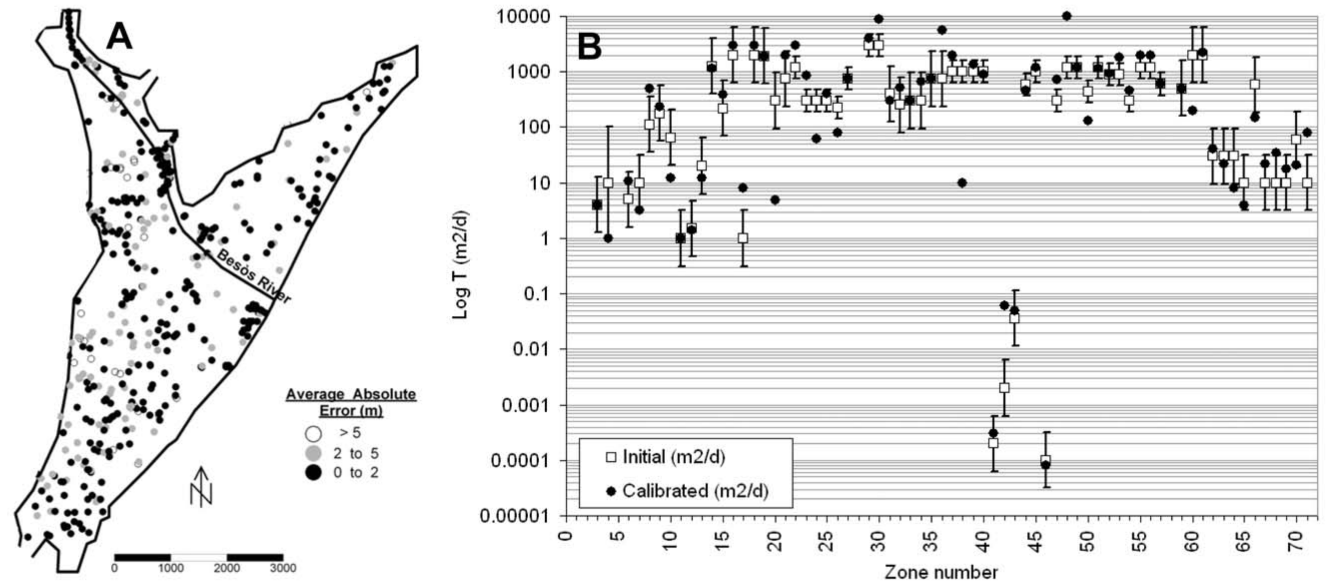

FIGURE 12 | A) Map of average error rate. Error values are indicated in meters. B) Graph showing the previous Transmissivity values versus the final calculated values. The vertical bars represent the assumed standard deviation for previous Transmissivity values.

this study because coastal and deltaic depositional systems record relative base-level changes. By contrast, in continental environments, the difficulty of identifying key surfaces (*i.e.,* sequence boundaries, transgressive or maximum flooding surfaces) rules out sequence stratigraphic analysis. In coastal and deltaic systems, the delta front, which is made up of coarse-grained deposits arranged in continuous and extensive bodies, constitutes the main aquifer unit, as in the Besòs delta. This facies association is most sensitive to relative base-level fluctuations and, as a result, sequence stratigraphic analysis is necessary to characterize aquifers in this type of depositional systems.

The geological model

In the emerged part of the Besòs delta, an average of about 22 boreholes per km^2 was available. In this very densely sampled scenario, a deterministic reconstruction of the defined geological units was considered as the best approach to interpret the most relevant sedimentological heterogeneities in the delta for a regional scale. Although more detail can be captured when modeling sedimentary heterogeneity at the scale of facies distribution, the design of the hydrogeological model in the Besòs delta introduced an accurate discretization of the hydraulic properties taking into account the internal heterogeneity of the geological units defined, *i.e.* facies distribution within facies associations.

Nevertheless, despite widespread sampling in the Besòs delta and despite the application of sequence stratigraphy, the nature and variability of proximal-to-transitional facies in the regressive systems tract of the Postglacial sequence introduced some uncertainty into the correlation process. In this zone, fine sediments frequently alternate with coarse-grained deposits, which made it difficult to differentiate between coarse sediments of the delta plain (channel fill deposits) and those of the delta front. In addition, the alluvial wedges, which are derived from the surrounding reliefs and are locally connected to the delta front body, make the delimitation of the stratigraphic units more uncertain. Moreover, the identification of the limit between the Pleistocene and the Postglacial sequences in the proximal deposits of the delta plain was prevented by the absence of sedimentary surface expressions. By contrast, characteristic lithologies and sequence stratigraphic significance were clearly defined in the marine deposits of the delta.

In outcropping depositional systems, correlation in continental environments can be carried out more effectively because of the availability of geological data (López-Blanco, 1996; López-Blanco *et al.*, 2000a, b), which enabled us to improve the 2D and 3D modeling of the heterogeneous media (Cabello, 2010).

As for the onshore-offshore correlation, large uncertainties should also be taken into account for the positioning of some surfaces and systems tracts owing to the scarcity and nature of the offshore data. One example of this is the identification of the lower sequence boundary defined onshore (SBII), which is probably a surface where other sequence boundaries coalesce offshore.

Another related uncertainty is the distribution of the geological units, within the offshore part of the model, that were defined by our conceptual understanding of the system and the offshore-onshore correlation of system tracts and surfaces.

Applicability of the workflow modeling

Although several groundwater flow and transport models have already been developed for the main and the upper aquifers in the Besòs delta (Vázquez-Suñé and Sánchez-Vila, 1999; Ondiviela, 2003; Vázquez-Suñé *et al.*, 2005; Ferrer, 2005; Tubau *et al.*, 2009; De Buen, 2009), these models did not take into account the lower aquifer or its interaction with the whole system. The hydrogeological model of the Besòs delta presented in this paper is a considerable improvement on the aforementioned contributions because of a better geological characterization and the incorporation of the lower aquifer. Moreover, given that the calibration of the hydrogeological model resulted in a robust solution with recalculated hydraulic values that were consistent with the geology of the delta, it may be assumed that the hydrogeological model validates the geological model. An unrealistic geological model as a basis for hydrogeological modeling would hamper the calibration of the hydraulic properties.

CONCLUSIONS

The application of sequence stratigraphy enabled us to develop a consistent 3D geological model of the basin, which provides valuable insights into the distribution of hydraulic parameters.

As a result of the significant improvement in the characterization of the geological heterogeneity of the Besòs Delta Complex, the lower aquifer was incorporated into the model, which further improves our understanding of the hydrogeological characteristics of the delta.

The consistency of the hydrogeological model validates the geological model and demonstrates the definite advantages of the methodology used in our study. This workflow modeling can be used to design and optimize hydrogeological modeling in similar settings, especially in urbanized areas where an effective management of groundwater is essential because of the subsurface infrastructures and the high population density.

Finally, the modeling platform used enabled us to structure all the available data and to set up an updatable model database, which makes this model ideal for future updates and downscaling.

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