Sequence Stratigraphy as a tool for water resources management in alluvial coastal aquifers: application to the Llobregat delta (Barcelona, Spain)

Desiré Gàmez Torrent

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CHAPTER 4: The role of geology in seawater intrusion and the vulnerability of Quaternary alluvial aquifers

PhD Thesis

Department of Geotechnical Engineering and Geo-Sciences (ETCG)
Technical University of Catalonia (UPC)
Supervisors:
Dr. J. Antonio Simó Marfà
Dr. Jesús Carrera Ramírez
Tutor:
Daniel Fernández García

HYDROGEOLOGY GROUP
TECHNICAL UNIVERSITY OF CATALONIA

geomodels
centre mixt d'investigació

Hydrogeochemistry group

Chapter 4

The role of geology in seawater intrusion and the vulnerability of Quaternary alluvial aquifers

Intensive human activities are generated in coastal plains and deltas, which poses a risk to both the quantity and the quality of groundwater resources. Many coastal aquifers are affected by seawater intrusion caused by pumping (fig. 4.1). Appropriate water management is necessary to protect, conserve and restore these aquifers (Abarca et al., 2006; Custodio, 2002; Vazquez-Suñé et al., 2006; WFD, 2000). Thus, it follows that comprehensive geological models are indispensable.

The typical deltaic hydrogeological conceptual model consists of two aquifers, an unconfined upper or shallow aquifer and a confined lower or deep aquifer. The two aquifers are separated by a silt and clay layer of low to medium permeability. The thickness of this aquitard normally pinches out towards the edges of the basin. As result, the two aquifers become connected at some distance inland (Gómez et al., 2003) at a point we shall term aquifer divide. The inland connection ensures a continuous inflow of water. The low permeability aquitard protects the deep aquifer from surface activities, with the result that this aquifer is generally regarded as ideal for exploitation. The most obvious pollution source in this deep aquifer is seawater intrusion.

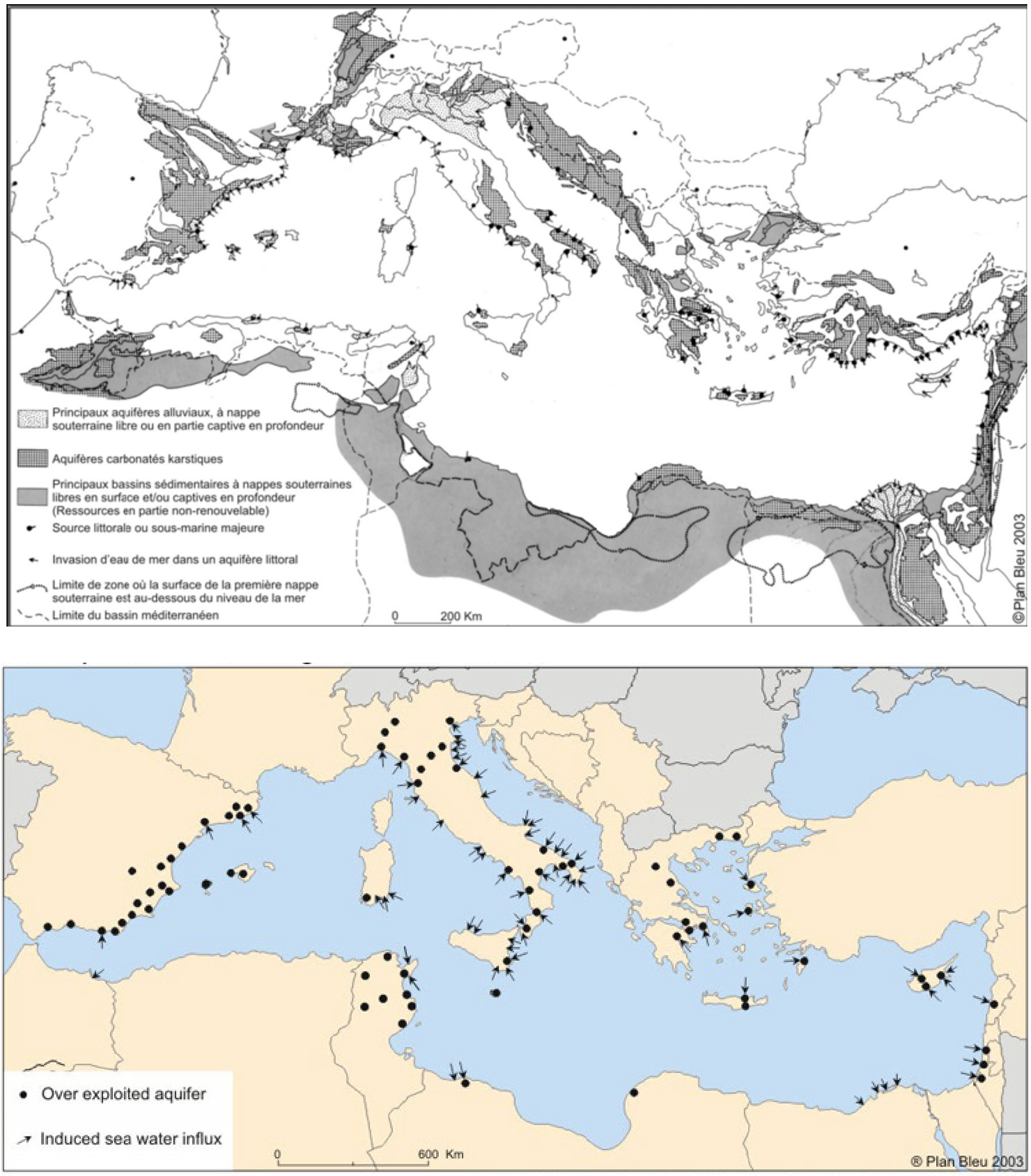

Figure 4.1: Above, Mediterranean coastal aquifers (Plan Bleu, 2004) and, below, identified over-exploited aquifers and sea water intrusion sites (karstic and alluvial aquifers).

The response of seawater intrusion in deep deltaic aquifers is somewhat erratic. Some of these (e.g. Llobregat or Tordera deltas, see fig. 4.2) become salinized in response to pumping (Abarca et al., 2007a; Falgàs, 2007; Vazquez-Suñé et al., 2006). Other deltas can sustain significant pumping rates prior to salinization (e.g. Ter, Fluvià-Mugà, Latium, see fig. 4.2) (Mas-Pla et al., 1999; Montaner et al., 1996). Yet others display large salinized portions even without pumping (Bayó et al., 1997). It may be surmised that the differences in the response of seawater intrusion to pumping are linked to differences in the extension and nature of the aquifer connection to the sea. If an aquifer is well connected, it will salinize quickly when pumped, and viceversa.

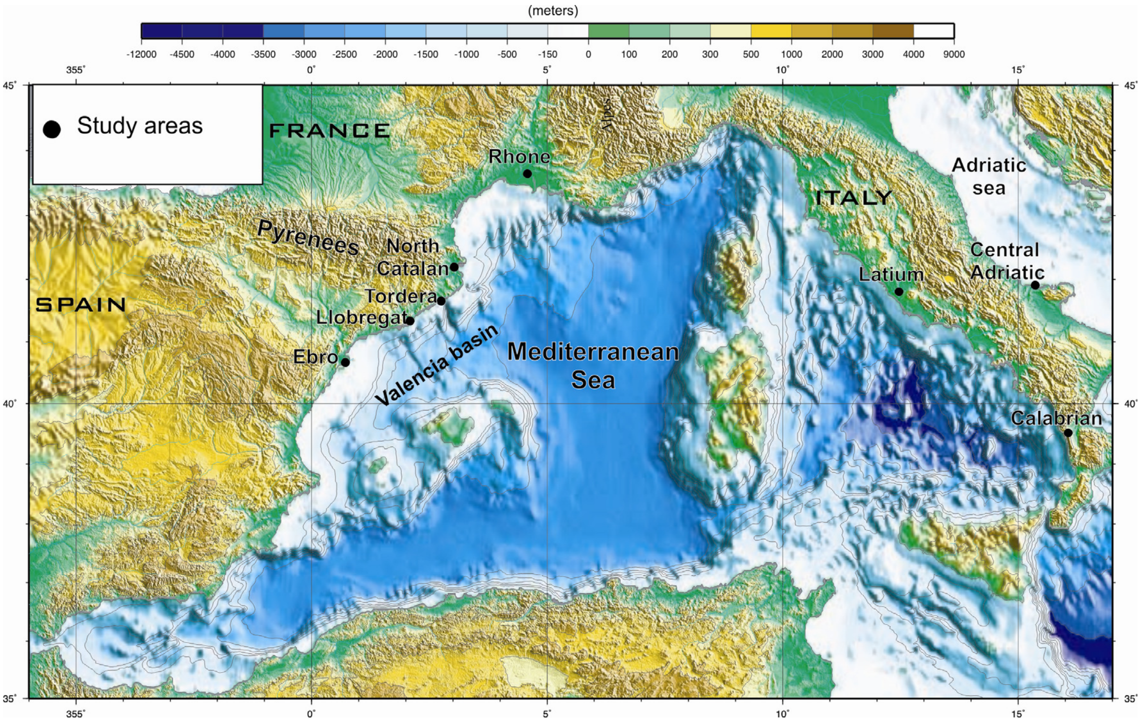

Figure 4.2: Map of the Western Mediterranean shows the onshore topography and sea floor bathymetry along the continental margin morphology (white interval, 0 to -150m). Alluvial coastal systems discussed in the text are also displayed. Modified from Rabineau (2001).

The characterization of the connectivity demands a sound knowledge of geology and hydraulics both onshore and offshore. Hydrogeologists typically focus on the onshore portions of aquifers (eg. Abarca et al., 2007a; Aguzzi et al., 2006; Falgàs, 2007; Iribar et al., 1997; Mas-Pla et al., 1999; Noell et al. 2004). However, the identification of the potential intrusion pathways is not easy given the lack offshore data (Mulligan et al., 2007). There have been few studies on the offshore continuity of the onshore aquifer geometries in coastal sediments (Edwards and Evans, 2002; Edwards et al., 2002; Ehman et al., 2000).

A model of the Llobregat delta is presented in Chapters 2 and 3. One question that remains to be resolved is whether such a model accounts for the seawater intrusion in this Delta. Moreover, given the similarity of delta processes, it is reasonable to assume that the lessons learned in the Llobregat delta could be extended to other deltas. To address this premise, we analyzed general deltaic geometries and local factors in the deltas shown in figure 4.2.

The aim of this chapter is to find out how local geological factors control the vulnerability of seawater intrusion in Quaternary coastal aquifers. To this end, the general features of Quaternary deltas are summarized. Then, we analyze the local geological factors that account for the seawater intrusion.

4.1. Quaternary delta conceptual model

4.1.1. Introduction

Deltaic systems are controlled by feedback processes involving two main factors: accommodation space and sediment supply (fig. 4.3). The accommodation space is defined as "the space available for potential sediment accumulation". This space is produced by the combination of movements of: (1) the sea surface, which is controlled globally by eustasy, and (2) the sea floor, which is controlled locally by tectonics or/and sediment loading. These factors combine to create or destroy accommodation space (fig. 4.3). The filling of this space depends on the rate of sediment supply in relation to changes in accommodation space. Sediment supply is in turn controlled by climate, the tectonics in the source area, and human activity in the Holocene.

Two sedimentary patterns can be identified in most deltas: the upper one (Postglacial) and the lower one (Pleistocene). These are separated by a regional erosional surface (SB I, in figs. 4.4a and 4.4b). These regional erosional surfaces correlate with glacio-eustatic sea-level falls and are interpreted as sequence boundaries (SB) (Chiocci et al., 1997, Chiocci, 2000; Ridente and Trincardi, 2002; Trincardi and Correggiari, 2000). Planar surfaces are also identified and attributed to turn arounds of retrogadational parasequences, deposited under conditions of sea level rise, and progradational parasequences, deposited under high sea-level conditions (fig. 4.4a and b). This surface is interpreted as a maximum flooding surface (mfs, fig 4.4, Catuneanu, 2002).

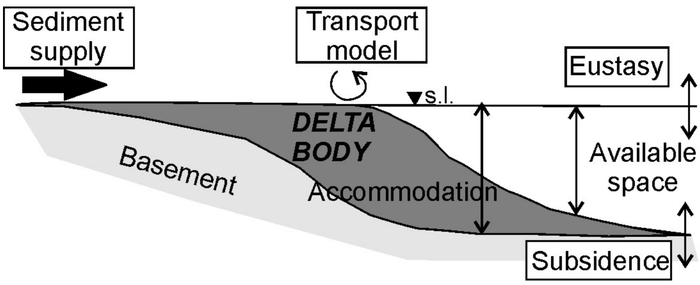

Figure 4.3: Main controlling geological factors in the deposition of the sediments; 1) eustatism, 2) basement movement (subsidence by tectonics or compactation), 3) variations in sediment supply (modified from Rabineau, 2001).

4.1.2. Postglacial depositional pattern

Postglacial materials were deposited after the last sea level minimum. They correspond to the modern deltas (fig. 4.4b). The bottom of the postglacial deposits coincides with the erosional surface (SB I, fig. 4.4) formed during the last glacial maximum (LGM). During low sea-level conditions (LST) coarse sediments were deposited as incised valley fills and amalgamated fluvial channels in non-marine successions (Fc). Fine sized materials were sedimented as aggradational and progradational coastal and marine deposits interpreted as prodelta facies (P, figs. 4.4a and 4.5a) (Foyle and Oertel, 1997; Posamentier and Allen, 1999; Saito et al., 1989). These deposits covered the erosional surface (figs. 4.4 and 4.5). Under these conditions, the shoreline was displaced to the shelf break formed during the earlier falling stage (section 4.1.3.).

After the LGM, the rapid rise in the sea-level produced a retreat of the coast (fig. 4.5c). As a consequence the depositional systems retreated in inland. These movements helped the waves to rework the tops of the earlier deposits (fig. 4.5c). The resulting sediments are known as the transgressive systems tract (TST). They can be recognized by the typical retrogradational stacking pattern (fig. 4.4a), which consists of overall fining-upwards profiles within non-marine to marine successions. The typical onshore sedimentary environment is made up of sand and gravel layers interpreted as a beach complex (B, fig. 4.4a). The coarse materials grade to finer deposits seawards (O, fig. 4.4a). In seismic records, these deposits show a chaotic and subparallel sheet seismic configuration (fig. 4.5a) (Saito et al., 1989). It should be noted that the large increase in accommodation space may not be matched by sediment transport. These deposits are capped by maximum flooding surface (mfs, Posamentier and Allen, 1999).

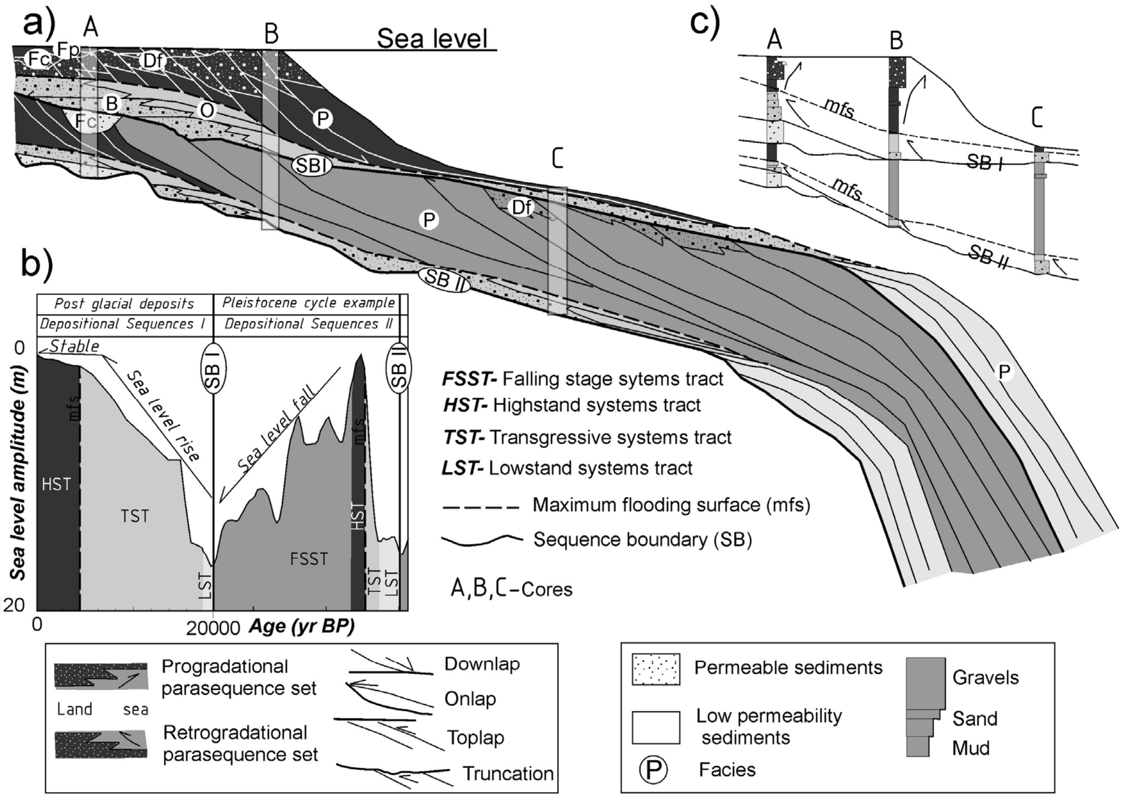

Figure 4.4: Conceptual model sedimentary patterns in Delta. (**a**) Facies distribution, systems tract interpretation, the representation of the sequence boundary and the position of the cores are displayed in the conceptual model (**b**) The two sedimentary patterns distinguished (Postglacial and Pleistocene), the location of sequence boundaries (SB) and the position of the systems tract in sea level curve are also represented. (**c**) A schematic correlation between representative cores is also displayed. Coarse sediments in transgressive and upper highstand deposits are considered as potential aquifers. Facies nomenclature; Fc: Fluvial channel; Fp: Flood plain and swamp; Df: Delta front; P: Prodelta; B: Sand and gravel beach; O: Offshore.

The sea level rise decelerated after 6500yr BP (Chapter 3; Fernandez-Salas et al., 2003; Zazo et al., 1996). This led to a decrease in the accommodation space and facilitated the progradation of the deltas (Stanley and Warne, 1994). From bottom to top it is possible to distinguish prodelta (P), delta front (Df), fluvial channel (Fc) and flood plain and swamp (Fp) (fig. 4.4). These deposits are easily interpreted from cores and seismic profiles. They are known as highstand systems tracts (HST). The HST delta succession displays interfingering geometries between delta front (Df, fig. 4.4) and fluvial system (Fc-Fp, fig. 4.4), and the prodelta composed of muddy distal facies (P, fig. 4.4). The number of the interfingering geometries in the Holocene delta depends on the relative influence of autocyclic factors such as neotectonic activity and fluctuation in sediment supply (Barriendos and Martin-Vide, 1998; Goy et al., 2003; Liquete et al., 2004; Thorndycraft and Benito, 2006a; Thorndycraft and Benito, 2006b; Trincardi et al., 2004; Chapter 2), and allocyclic factors such as millenial-scale climatic and fifth-order sea-level cycles (Fernandez-Salas et al., 2003; Chapter 2).

From the hydrogeological point of view, the coarse sediments deposited during the transgression systems tract constitute a good aquifer due to their high continuity and permeability. Delta front and fluvial channels in highstand systems tracts form the shallow aquifers in the current delta plains, and display interfingering geometries with the prodelta aquitards (fig. 4.4). Fluvial facies present variable permeabilites depending on the muddy matrix content. Offshore and prodelta facies show low permeabilities, which correspond to the aquitards in most delta plains (Iribar et al., 1997; Falgàs, 2007; Gómez et al., 2003; MOP, 1966; PHOP, 1985; Shamsudduha et al., 2007). The interfingering relationship of the deposits is usually regarded in hydrogeology studies as a low permeability zone. However, prodelta facies can be highly anisotropic. Continuous sand layers, slightly tilted towards the progradational slope, provide subhorizontal permeabilities. The prodelta fine deposits yield very low subvertical permeabilities.

4.1.3. Pleistocene depositional pattern

The studied Pleistocene deltas are complex. Only a simplified conceptual model is described here. The bottom of each Pleistocene pattern consists of erosional truncations that define the boundary of the earlier depositional sequence (SB II, fig.4.4). Lowstand and transgressive facies patterns similar to those of postglacial patterns were deposited immediately above the SB II. The most important difference between Pleistocene and postglacial architecture lies in the highstand delta and the deposition of the falling stage deposits (FSST, fig. 4.4). Following the highstand deposits, the accommodation space decreased, and the FSST and LST sediments were deposited (fig.4.5b). Deltaic deposition during sea level fall was caused by the river eroding down to the new sea level position and mobilizing the basement (earlier HST and FSST deltas, fig. 4.5b, Plint et al., 2000). Thus, sediment supplies came from earlier sediments and the river basin. These falling stages caused considerable erosion, reworking of sediment and depositional gaps represented by internal erosions.

Pleistocene highstand generally consists of progradational clinoforms with wedge shapes pinching out seawards (fig. 4.5b). These sediments have been interpreted as a muddy to sandy shoreface with reworked sediments and fauna (Hernandez-Molina et al., 2000). Falling stage deltas consist of progradational clinoforms with wedge shapes pinching out landwards (Hernandez-Molina et al., 2000). HST, FSST and LST show regressive wedge geometry (progradational reflectors, figs. 4.5a and 4.5b) generally characterized by muddy lithologies (P, fig. 4.4a).

From the hydrogeological point of view, HST and FSST result in low permeability aquitards with potential local permeable deposits (Df, fig. 4.4a). As in the postglacial conceptual model, the pleistocene transgressive deposits display high permeability and represent the deeper aquifers.

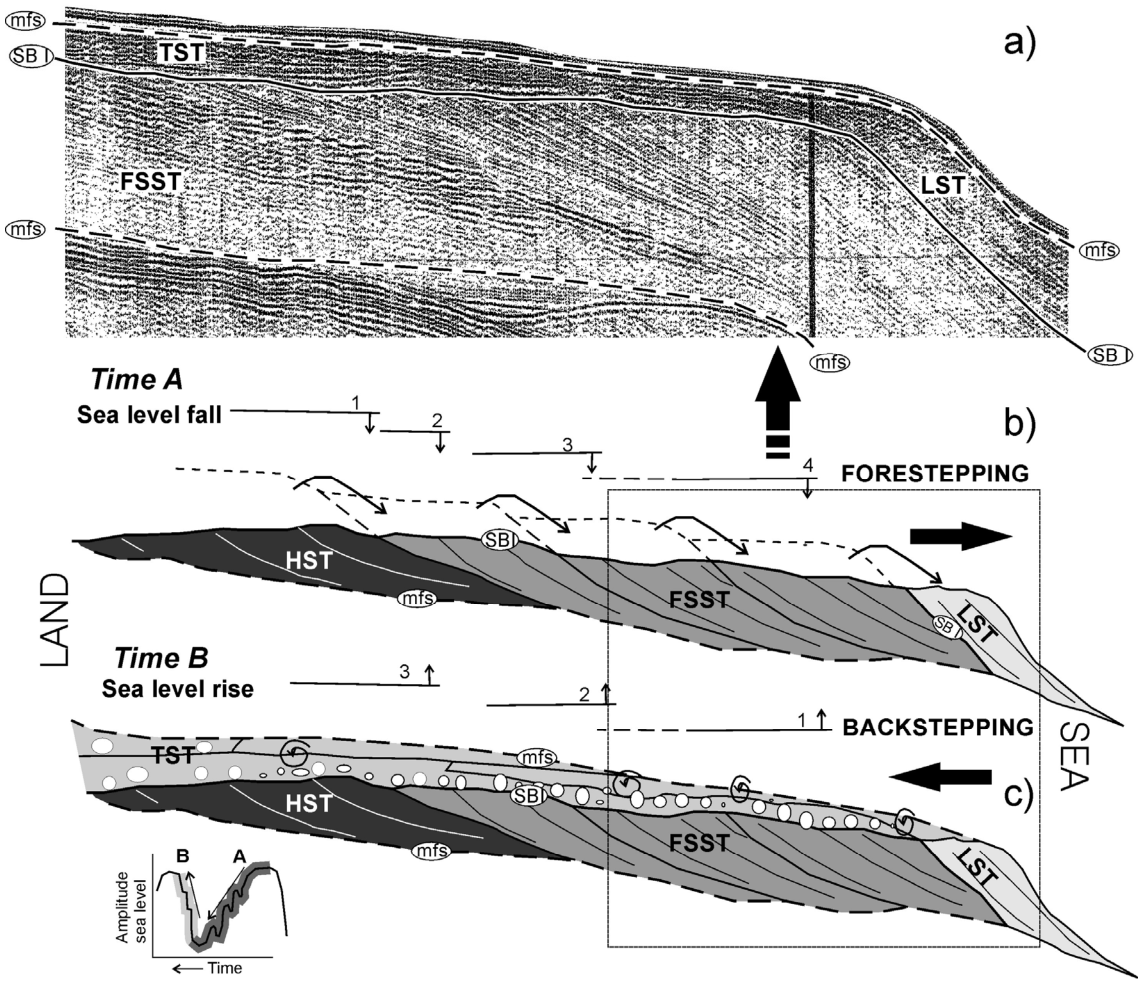

Figure 4.5: (**a**) Seismic response of the erosional (SB) and planar surface (mfs), and falling stage (FSST), lowstand (LST), transgressive (TST) deposits. (**b**) The formation of the Highstand (HST), falling stage and lowstand deposits under conditions of high, falling and low sea level, respectively. Dashed lines indicate the eroded sediments. (**c**) The transgressive sediments were formed by the reworking of the tops of earlier sediments owing to the wave-base erosion accompanied by landward migration of the shoreline. Modified from Rabineau et al. (2001).

4.2. Local geological controls: Implication for sea water intrusion

4.2.1. Introduction

From the hydrogeological point of view, section 4.1 implies that deltaic systems consist of a shallow aquifer and one or several deep aquifers. These aquifers are separated by silt and clay layers of low to medium permeability. The shallow aquifer corresponds to coarse postglacial highstand deposits and the deep aquifers to the postglacial and pleistocene transgressive deposits in most delta plains in the Mediterranean (Aguzzi et al., 2006; Noell et al., 2004). Silt and clay layers between the shallow aquifer and the postglacial transgressive aquifer correspond to offshore and prodelta facies deposited during transgressive and postglacial highstand periods (fig.4.4a). Silt and clay layers between transgressive deep aquifers represent the HST and FSST deposits.

Well protected by the prodelta confining unit, the transgressive aquifers display high permeabilities and good water quality. It is not surprising that these aquifers are actively exploited for fresh water. However, these aquifers may be affected by seawater intrusion.

Recent offshore seismic profiles of the Pacific and Atlantic Quaternary shelves have recognized palaeochannels or buried ancient stream channels that represent potential pathways for seawater intrusion (Abarca et al., 2007b; Edwards and Evans, 2002; Edwards et al., 2002; Gaswirth et al., 2002; Iribar et al., 1997; Krantz et al., 2004 and Mulligan et al., 2007). These palaeochannels are interpreted in this study as transgressive deposits. It is therefore necessary to focus our attention on their vulnerability to seawater intrusion.

Seawater intrusion due to natural or pumping conditions has been differentiated. Under natural conditions, intruded seawater is almost always stagnant. Therefore, it may be assumed that water pressure depends exclusively on depth below sea level. At the interface, this pressure must equal the weight of fresh water above the interface. This leads to the well known Ghyben-Herzberg principle, which states that the depth of freshwater below sea level is forty times its head (Ghyben, 1889; Herzberg, 1901). By contrast, pumping induced the flow of both fresh and seawater with the result that it can no longer be assumed that the seawater is static. Thus, the Ghyben-Herzberg principle is not applicable. Nevertheless, as stated above, significant amounts of seawater will flow into the aquifer only if the aquifer is well connected to the sea.

The effect of these two principles is summarized in figure 4.6. Under natural conditions, the salinization status of the aquifer depends on the water level at the aquifer divide. Freshwater flows towards the sea, preventing salinization of the deep aquifer if the head at the aquifer divide is higher than the depth of the transgressive aquifer (i.e, if $h>z/40$, where h is head at the aquifer divide and z is the depth of the exit point, See fig. 4.6a2). This is often the case in small and steep deltas, such as the Llobregat or Tordera deltas. On the other hand, widespread salinizition occurs if head at the aquifer divide is lower than the depth of the transgressive aquifer (i.e, if $h<z/40$). Thus, the seawater intrusion penetrates so that $z_d=40 \cdot h$ (fig. 4.6a1). This is the case of large deltaic systems, such as the Ebro or Rhone River deltas (Bayó et al., 1997; Dörfliger, 2003). These deltas are flat and the river is deeply incised, which ensures a low head at the aquifer divide and allows the penetration of a wedge of seawater into the river during periods of low flow (Ibañez et al., 1997).

Under pumping conditions, however, the seawater penetration depends on the connectivity of the aquifer to the sea. If transgressive aquifers are well connected to the sea, the aquifers are more vulnerable to seawater penetration (fig. 4.6 b1). But if the transgressive aquifers are poorly connected to the sea, the aquifers are less vulnerable to seawater penetration (fig. 4.6 b2).

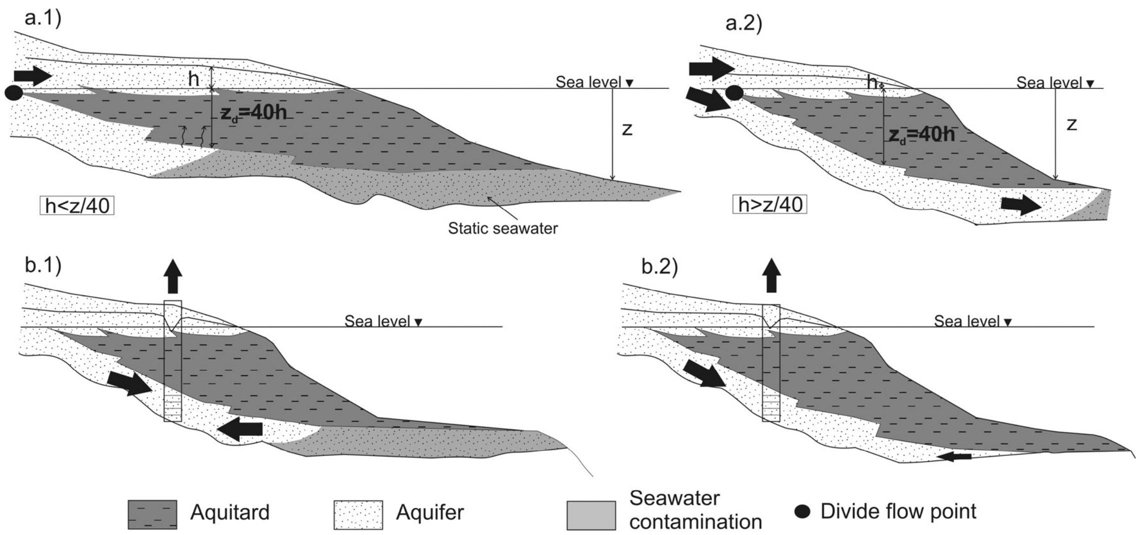

Figure 4.6: **a)** Flow under natural conditions where sea water intrusion is controlled by relative slopes of the phreatic surfaces TST aquifers. **a.1)** Low slope of the phreatic surface and TST aquifer; **a.2)** High slope of the phreatic surface and TST aquifer. **b)** Flow under pumping conditions (only for a.2). **b1)** Well connected; **b2)** poorly connected.

In short, transgressive aquifers are potential pathways for seawater contamination under pumping conditions. However, the preservation of these transgressive aquifers and the spatial and vertical stacking of the depositional sequences at both regional and local scales are controlled by local geological factors. Local factors such as accommodation changes and the duration of transgressive intervals (Hernandez-Molina et al., 2000b) may play a bigger role than the influence of background sea-level (Ritchie et al., 2004). These local factors envolve subsidence or uplift and sediment supply. The total subsidence enables the creation of considerable accommodation space, which is filled with sediment. In areas affected by tilting, where the distal margin strongly subsides compared with proximal margin and/or coast, the degree of preservation depends on the ratio of subsidence to regional uplift. In summary, subsidence (or uplift) together with the sediment influx during an increase in accommodation is instrumental in the preservation of transgressive aquifers.

4.2.2. Seawater intrusion in poorly preserved transgressive deposits

Most of the Quaternary deltas affected by uplift display poor permeable transgressive deposits (Ercilla et al., 1994; Labaune et al., 2005a; Ricci Ricci Lucchi et al., 2006; Tesson et al., 2005). They are mainly composed of regressive wedges e.g. North Catalonia, Calabria; Latium, Adriatic shelves (table 4.1; Amorosi and Milli, 2001; Chiocci et al., 1997; Chiocci, 2000; Ercilla and Alonso, 1996; Ercilla et al., 1994; Ridente and Trincardi, 2005). In areas with significant uplifting, the earlier deposits were eroded during each sea level cycle, suggesting that the rate of tectonic uplift and hence the tilting of the Quaternary margin are the key factors in the continuity of the preserved transgressive deposits.

The North Catalonian shelf (table 4.1; fig. 4.2) may be regarded as a good example of stratal pattern in the tectonic context. It displays two Quaternary depositional sequences in the delta plain (Montaner et al., 2004), which are poorly preserved on the inner shelf. The Holocene-Pleistocene delta displays a vertical stacking of well developed regressive deposits from middle continental shelf to the upper continental slope, which Ercilla (1992) attributes to shelf-off subsidence (fig. 4.7). Their poor preservation is due to the Pyrenean uplift, which produced the tilting of the regressive deposits on the middle to outer shelf (fig. 4.7, Ercilla, 1992). Uplift together with a probable decrease in sediment supply during sea level rise leads to the virtual disappearance offshore of the transgressive systems tract (Ercilla et al., 1996). Nevertheless, transgressive deposits are preserved onshore (Montaner et al., 2004).

Similar stratal patterns are observed on the Adriatic, Calabria and Latium shelves, with a strong to moderate uplift context and tilting of the margin (table 4.1; figs. 4.2 and 4.11; Chiocci et al., 1997; Chiocci et al., 2000; Ridente et al., 2005; Ridente et al., 2006). For example, along the Adriatic margin, the 3D sedimentary architecture is highlighted to determine the limits of the aquifer. In figure 4.8b, continuity of the transgressive deposits is observed. Nevertheless, these deposits appear truncated or deformed owing to a structural high in the northwest (fig. 4.8a).

In this context, postglacial transgressive deposits are preserved but are thinner (figs. 4.7 and 4.8). The most significant observation in the seismic profiles from Italy and Northern Catalonia is that the postglacial deposits overlie the tilted pleistocene sequences. These are truncated by erosional surfaces in the last glacial maximum and generally display a sub-horizontal geometry (SB I, figs. 4.7 and 4.8). Pleistocene transgressive aquifers may be preserved, but tilted, which causes a break in the continuity of the aquifer (fig. 4.9). The very fine postglacial deposits above Pleistocene sequences contribute to the low hydraulic connection to the sea.

The hydrogeological implication of thin or absent postglacial transgressive deposits is obvious: onshore aquifers are well protected. This finding agrees with the observations in the North Catalan deltas (Ter, Muga and Fluvia deltas). Despite considerable exploitation, these deltas have not suffered seawater intrusion. Some chloride has been observed in the Ter Delta, but this is attributed to relict salinity within the postglacial prodelta deposits (Montaner et al., 1996).

Table 4.1: Characterisitcs of the onshore alluvial systems and shelves mentioned in the text (Liquete et al., 2004 and 2007; Chiocci et al., 1997; Amblas et al., 2006; Checa et al., 1988; Diaz et al., 1993; Falgàs , 2007; Gensous et al., 1996; Ridente et al., 2005; http://www.rev.net/~aloe/river/ .http://mediambient.gencat.net/aca/ca/aiguamedi/subterranies/fitxes_masses.jsp. (*) Distance between river mouth and shelf break

SITUATION			**PUMPING (hm3/any)**	**ONSHORE**				**OFFSHORE**			**NEOTECTONICS**
Main rivers	**Shelf**			**Basin Area (Km2)**	**River length (km)**	**Delta plain area (Km2)**	**Mean water discharge (m3 s-1)**	**Shelf wide (Km)**	**Offshore slope (degrees)**	**Shelf break depth (m)**	
Fluvia-Muga	North Catalonia	Spain	22	1,124/854	91/65	120	1.34/3.26	6-30	0.2-0.78	120-150	Moderately subsident margin. Horst and grabens on the shelf
Ter			25.2	3,010	208		12.13				
Tordera	Barcelona		37	878.8	59.3	4.2	0.73	5*		110	Strong subsidence margin
Llobregat			30.7	5,045.10	162.7	97	16.67	6.6*-20	0.3-0.7	90-95	Strong subsidence margin
Ebre	Ebre		0.1	85,708	982	320	410.42	70	0.305	130	Strong subsidence margin
Tiber	Latium	Italy	-	17,000 (Tiber)+hundreds	405	57	-	10-20	-	-	Moderate uplift in front Tiber, subsidence in the northern Latium
Calabrian			-	tens	-	-	-	1-8	-	-	Strong uplift
Central Adriatic			-	-	-	-	-	30-80	0.2-0.6	-	Uplift, horst and graben on the shelf
Rhone	Rhone	France	-	98,845	810	1,750	1,500	75	-	120-130	Regional seaward tilting of the wedges providing accommodation space to mid-outer shelf. Differential subsidence.

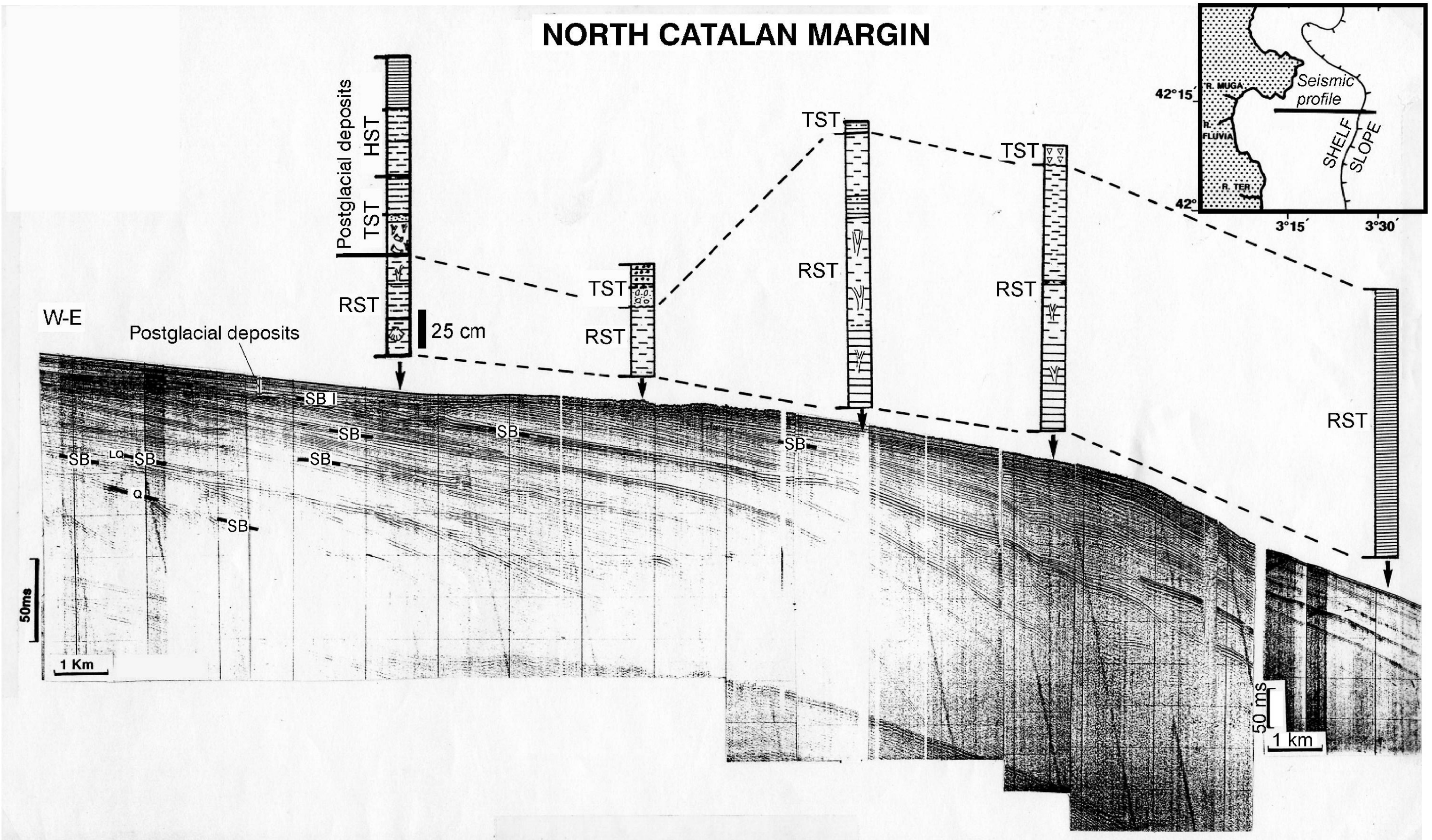

Figure 4.7: Dip seismic profile of the North Catalan shelf modified from Ercilla et al., 1992 (see location in figure 4.2). Pleistocene stratal pattern shows inclination due to Pyrenean uplift and thin transgressive deposits (represented by parallel facies). Representative cores along the shelf are interpreted using sequence stratigraphy concepts (RST=FSST+LST), postglacial thinner transgressive deposits (TST) and postglacial highstand prodelta facies (HST). Nomenclature: SB; Sequence Boundary, LQ; bottom of the late Quaternary, Q; Bottom of the Quaternary deposits.

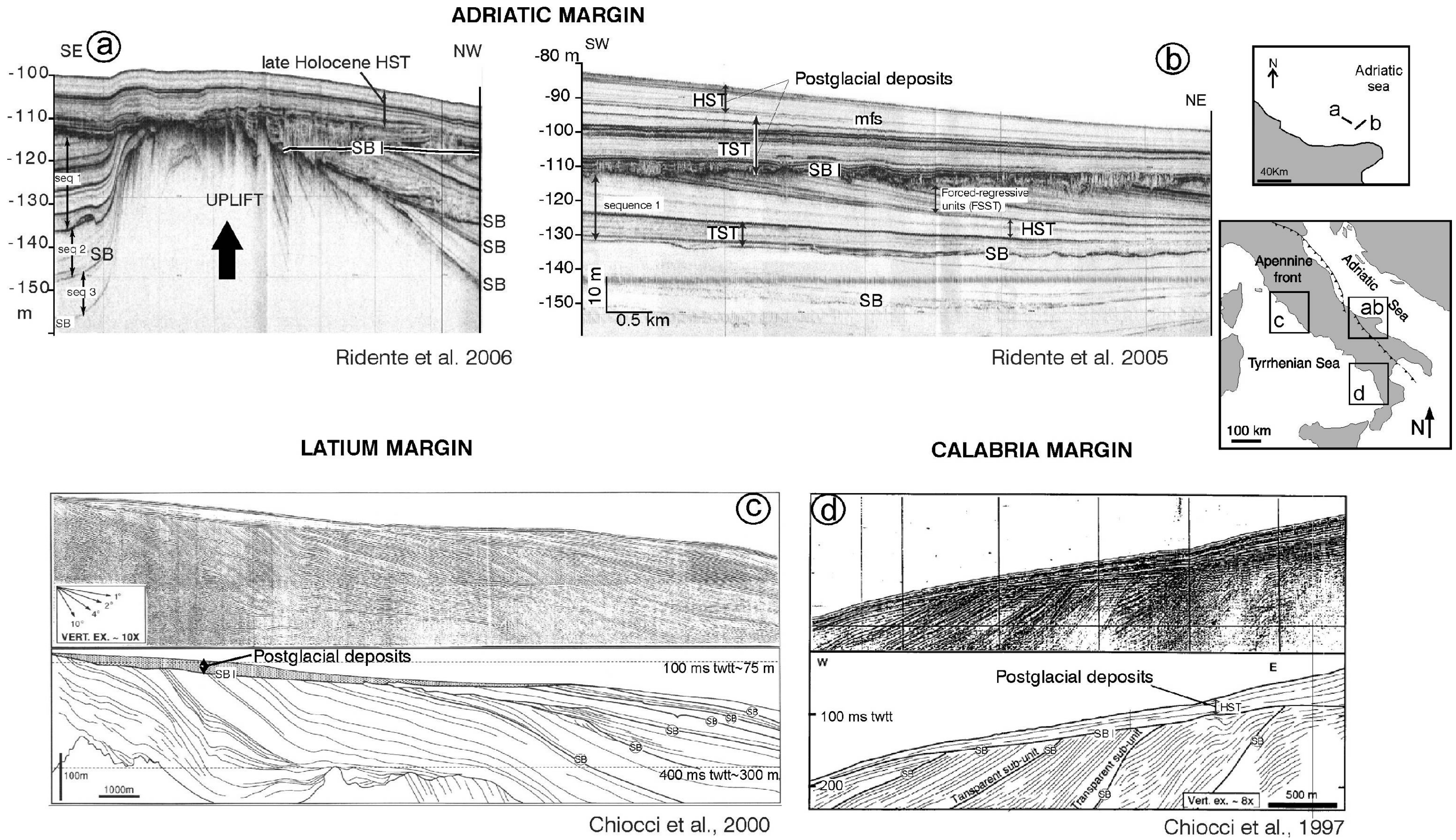

Figure 4.8: Seismic profiles of Italian shelves affected by tectonic activity (see location in figure 4.2). Sequence stratigraphic interpretation of parallel (TST) and oblique-tangential seismic units (FSST and HST) is also shown. Postglacial deposits overlie the tilted pleistocene sequences truncated by erosional surfaces in the last glacial maximum (SB I).

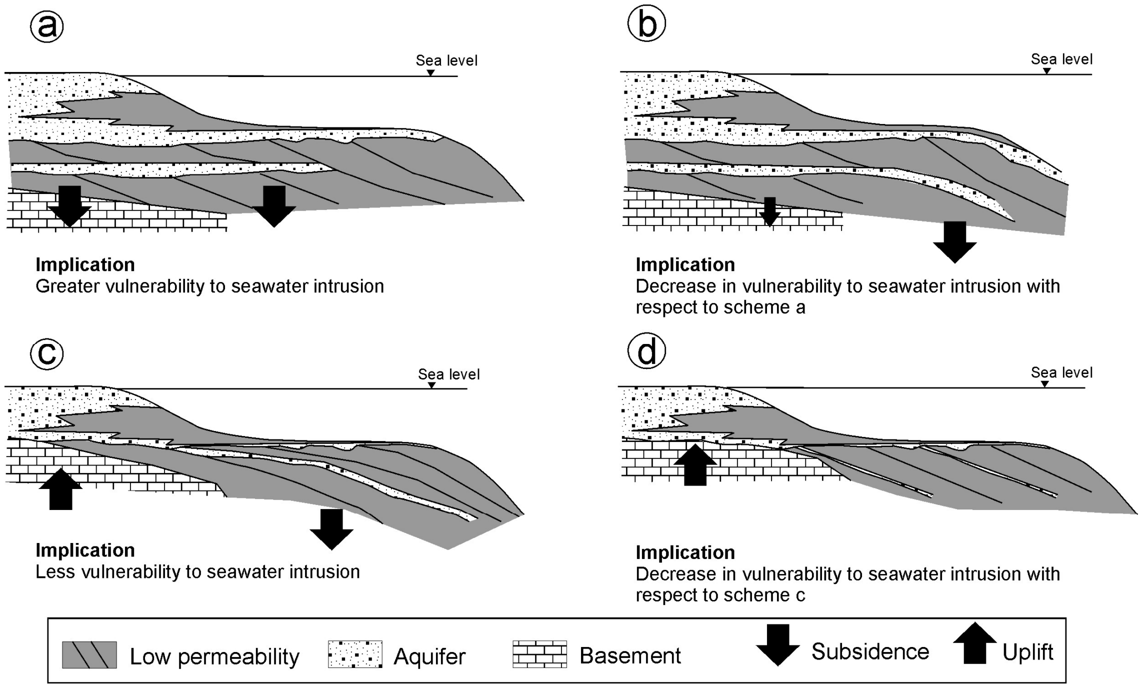

Figure 4.9: Schematic hydrogeological conceptual models considering the different scenarios put forward in this study. Scheme **a** refers to figure 4.10, general subsidence control. Scheme **b** refers to figure 4.11, differential subsidence control. Scheme **c** refers to figure 4.7, uplift onshore and subsidence offshore. Scheme **d** refers to figure 4.8bc, uplift onshore. Note that schemes a, b and c also consider some detritical input during sea level rise.

4.2.3. Seawater intrusion in well preserved transgressive deposits

The Quaternary records of continental margins affected by subsidence show well preserved transgressive deposits offshore (Diaz and Maldonado, 1990; Lobo et al., 1999; Lobo et al., 2002; Rabineau et al., 1998; Tesson et al., 2000). However, most of the delta plain transgressive deposits appear amalgamated, without interbedded silt layers (Cantalamessa and Di Celma, 2004; Massari et al., 1999; Zazo et al., 2003). Some deltas preserved onshore and offshore transgressive deposits. Of the deltas studied here, the Llobregat delta is the one with best preserved transgressive deposits. Thus, it may be regarded as a paradigm of continuous transgressive deposits.

The Llobregat Delta is a classic hydrological system affected by seawater intrusion. Seawater intrusion in this area since the 1960s has been documented by