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

UPC
HYDROGEOLOGY GROUP
TECHNICAL UNIVERSITY OF CATALONIA

geomodels
centre mixt d'investigació

Hydrogeochemistry
group

numerous studies (Abarca et al., 2006; Bayó et al., 1977; Custodio et al., 1976; Custodio, 1981; Doménech et la., 1983; Iribar et al., 1997; Manzano et al., 1992; Vazquez-Suñé et al., 2006). The Llobregat delta (table 4.1; fig. 4.2) is composed of a thick progradational deposit and thinner parallel units (fig. 4.10). The general sedimentary architecture displays a repetitive pattern consisting of regressive-stabilization-transgressive cycles bounded by three regional erosional surfaces. These regional erosional surfaces correlate onshore with three fluvial erosional surfaces (fig. 4.11). These surfaces are interpreted as sequence boundaries (SB I, II and III). Onshore, coarse lowstand and transgressive deposits fill these three regional palaeochannel systems. Offshore, the transgressive units are seen in seismic profiles as chaotic and subparallel-horizontal sheet facies in the southwest (fig. 4.10) and wedge geometries in the northeast (fig. 4.11). Transgressive deposits are covered with the regressive deposits (HST and FSST). The only HST deposit above transgressive deposits without a corresponding FSST component is the modern HST corresponding to postglacial deposits (DS I, figs. 4.10 and 4.11).

The excellent preservation observed in the Llobregat onshore-offshore delta may be ascribed to deposition in the highly subsiding half-graben area due to extensional listric faults (Morrot, Barcelona faults and minor faults, Chapter 3). This tectonic activity creates much accommodation space. Considerable accommodation space together with a large sediment supply during sea level, rise accounts for the good preservation of the transgressive deposits.

The preservation of the postglacial and Pleistocene sequences leads to a multi-layered aquifer system, consisting of transgressive subaquifers separated by confining or semiconfining layers (fig. 4.11) (Custodio et al., 2002). The continuous postglacial high permeability transgressive deposits throughout the delta plain-shelf-slope domain are known as the main aquifer of the Llobregat hydrogeological system (figs. 4.9, 4.10, and 11) (Vazquez-Suñé et al., 2006). The transgressive Pleistocene deposits are known as deep aquifers in the Llobregat system.

Chloride data from the main (postglacial) and deep (pleistocene) aquifers plotted in the onshore maps and vertical conductivity data show higher chloride concentrations in the main aquifer than in the deep aquifers (fig. 4.12). This is somewhat surprising as it runs counter to the conventional sea water intrusion models, which predict that seawater intrudes into the aquifer through the deepest portions of the aquifer. These peculiarities can be explained by the connection of the aquifers to the sea. The onshore-offshore continuity of the main aquifer provides a hydraulic connection with the sea, and facilitates seawater intrusion along the palaeochannels. However, deep aquifers appear to be disconnected from seawater (figs. 4.11 and 4.12), with the result that their salinity could derive from the main aquifer or relict seawater.

An illustration of the role of aquifer continuity in controlling seawater intrusion is provided by the intrusion finger south of the Morrot Fault (northeastern margin of the delta, fig. 4.12). This fault virtually disconnects the northern upper block from the southern block. Seawater intrusion occurs along the southern block. A deeper understanding of current intrusion sites is provided by the location of submarine canyons, which is discussed in the following section.

These seawater intrusion mechanisms account for hydrogeological data and seawater intrusion observations in the Llobregat delta (Bayó et al., 1977; Custodio, 1981; Custodio et al., 1976, 1989; Doménech et al., 1983; Iribar et al., 1997; Manzano et al., 1992; Vázquez-Suñé et al., 2006).

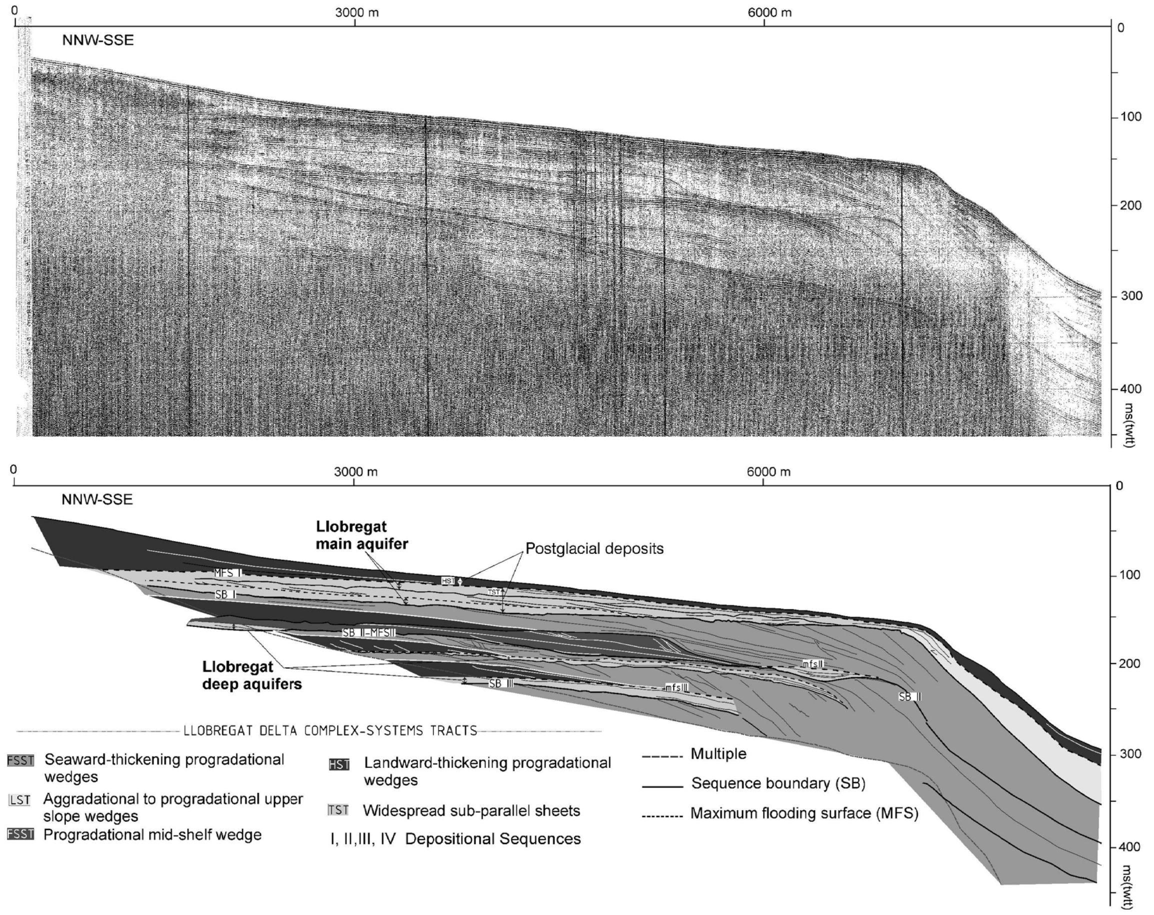

Figure 4.10: Uninterpreted (top) and interpreted (bottom) dip seismic profile of the Llobregat delta southwestern shelf. Sequence stratigraphy interpretation according to the associated sea-level trend is shown (Chapter 3). Transgressive permeable aquifers exhibit a continuous sub-horizontal-parallel structure. The postglacial transgressive aquifer is the main aquifer that supplies water to Barcelona and covers a large area from onshore to the slope (fig. 4.11). Depth is in two-way-travel time in milliseconds (approx 50 ms=38.75 m). Seismic profile is located in figure 4.11. HST-Highstand systems tract; TST-Transgressive systems tract; FSST- Falling stage systems tract; LST-Lowstand systems tract

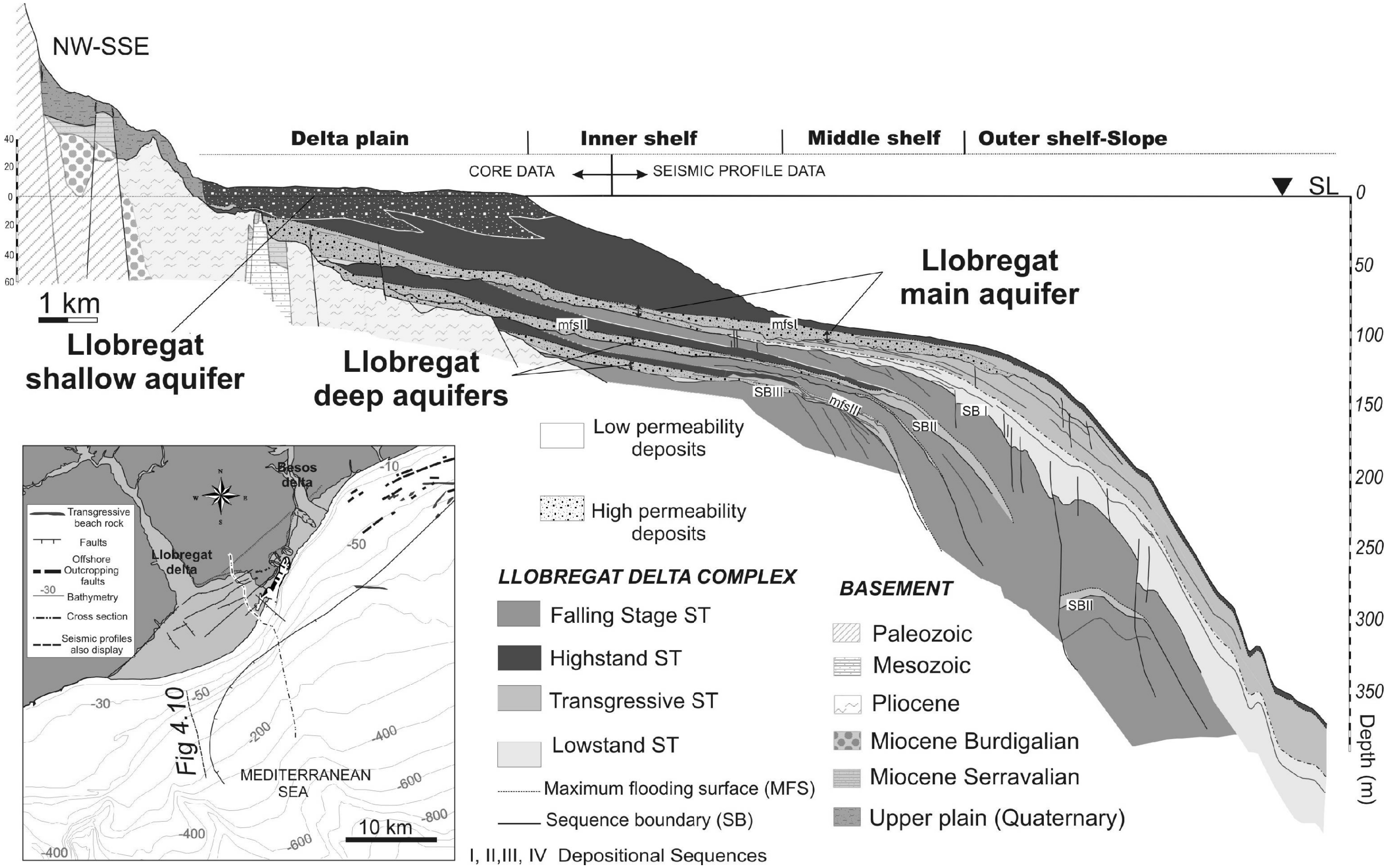

Figure 4.11: Onshore-offshore sequence stratigraphy interpretation, based on the correlation between onshore cores and seismic profiles along the northeastern Llobregat delta plain and shelf (Chapter 3). Transgressive permeable aquifers exhibit sub-horizontal-parallel shapes from onshore to middle shelf and wedge geometries to outer shelf-slope due to the growth faults. Coarse highstand aquifer interfingering geometries with the prodelta aquitards. Depth is in meters (m). Dashed lines in the map on the left depict the seismic profiles in this figure and figure 4.10. Bathymetric contours, faults and transgressive beach rocks are shown in the map (Chapter 3 and Liquete et al., 2007)

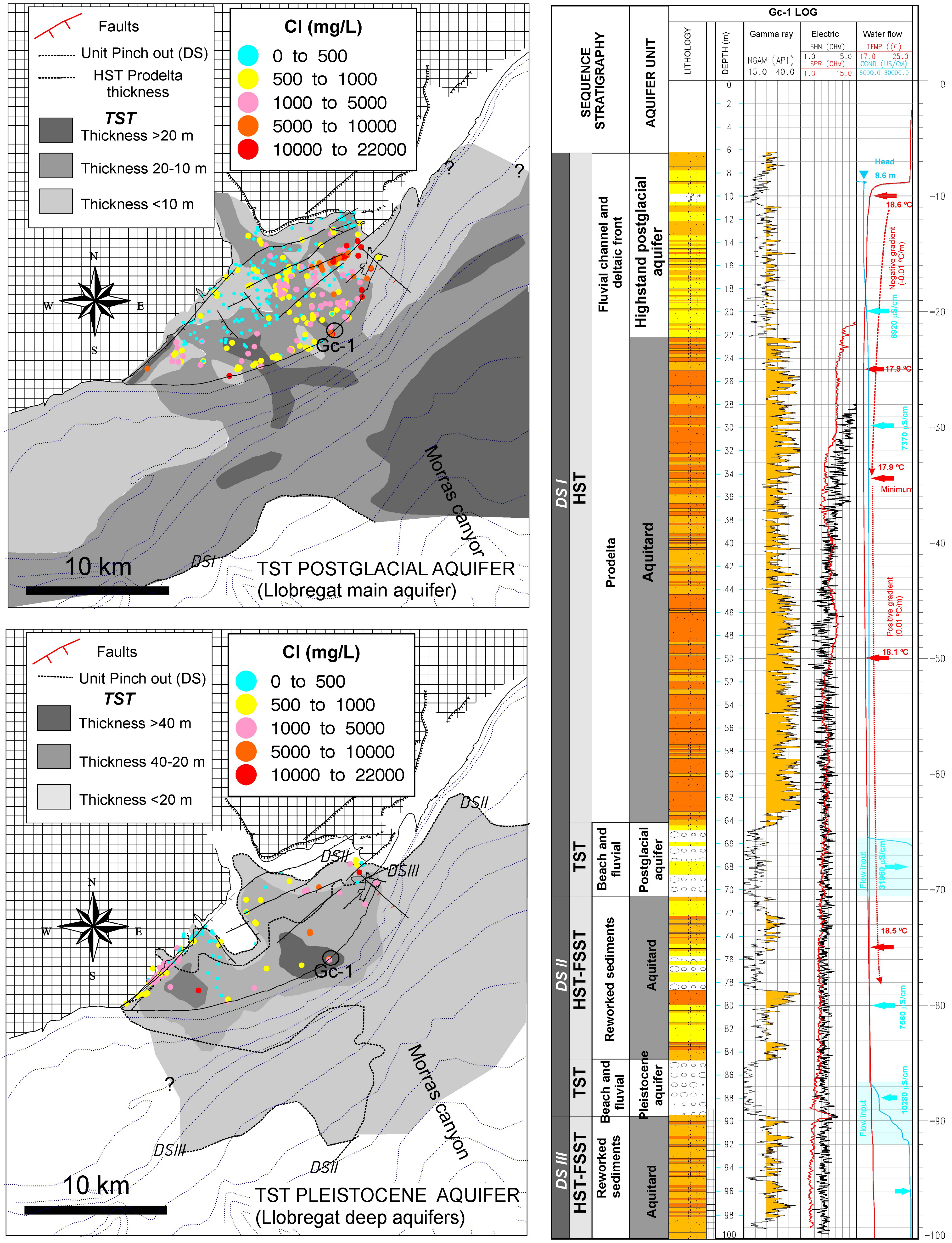

Figure 4.12: Sea water intrusion into the Llobregat delta. Note that the postglacial transgressive aquifer is more inversely intruded than the Pleistocene sediments. Note the chloride (mg/l) is concentrated along the Morrot fault and in the areas of greater thickness. Geophysics profile, sedimentary interpretation and hydrogeological information (included conductivity data) are also displayed (modified from ACA, 2003). DS: Depositional Sequences; HST; Highstand sytem tracts; TST; Transgressive systems tract; FSST; Falling stage. Note that seaward units in the map are also composed by sediments with low permeability (Chapter 3).

4.2.4. Thin prodelta thickness, submarine canyons and faults: mechanisms that expose the aquifers to the sea floor

The preservation of the transgressive deposits is one of the main factors in facilitating onshore-offshore connection. However, seawater intrusion into these transgressive aquifers also depends on other geological factors such as thin postglacial prodelta facies, submarine canyons and neotectonic faults. All these factors play a role in exposing transgressive deposits to the sea floor (Edwards et al., 2002). The aquifer most affected by these factors is the postglacial transgressive aquifer as it the one closest to the sea floor.

As regards the prodelta facies, the maximum thickness of the prodelta is located along the shoreline, pinching out offshore (fig. 4.11). The aquifer is vulnerable to seawater penetration if the postglacial trangressive deposits are well preserved (stratigraphically below the prodelta facies) and if the prodelta facies are absent or thin out seawards. This is the case of the Llobregat delta where the prodelta unit reaches a maximum thickness of 50m along the river mouth and the inner shelf (fig. 4.11), and thicknesses ranging between 10 and 20m along the margins. These deposits show a marked decrease in thickness to middle-outer shelf, reaching values of 4m. The thin Llobregat prodelta thickness offshore may allow the infiltration of seawater into transgressive deposits. The reduced thickness of the prodelta deposits may not be a critical factor by itself. The permeability of prodelta deposits is likely to be so small that it could offset the effect of the reduced thickness. However, a reduced thickness increases the risk of discontinuity of prodelta sediments, which would expose the transgressive aquifer to the seafloor.

As for the submarine canyons, some of these may have the head of the canyons close to the shoreline in narrow shelves. These canyons may erode the postglacial and pleistocene prodelta deposits, thus exposing the transgressive deposits to seawater. The Tordera deltaic system (North Catalan margin) is one of the most representative examples in the Mediterranean western margin (fig. 4.2 and 4.13). This delta displays a very narrow shelf with the Blanes submarine canyon head at -110m located less than 5km from the Tordera delta shoreline (table 4.1; fig. 4.13). The Blanes Canyon is deeply incised and it is one of the most prominent on the NW Mediterranean shelf (fig. 4.13) (Amblas et al., 2006). The Tordera delta shows well preserved postglacial transgressive desposits (Serra et al., 2007). In fact, there are three postglacial transgressive units on the inner-middle shelf, and transgressive deposits fill palaeochannels on the delta plain-inner shelf (Falgàs, 2007; Serra et al., 2007). The Tordera delta aquifer suffers sea water intrusion due to pumping (table 4.1). The main intrusion paths are related to an ancient palaeochannel that is oblique to the current Tordera River (Falgàs, 2007). Although observations are incomplete, they suggest that this channel may be exposed to the seafloor by erosion from the Blanes submarine canyon. A similar mechanism is observed in the Llobregat delta, where not all palaeochannels carry seawater inland (fig. 4.12).

Chloride maps from the main aquifer reveal a large intrusion site at the Morràs submarine canyon (figs. 4.12 and 4.13). This canyon is located 6.6 km from the mouth of the Llobregat river and coincides with a palaeochannel (fig. 3.9 and 4.12). Seismic profiles between the Foix and the Berenguera submarine canyons (fig. 4.13) show palaeochannel shapes probably filled with transgressive deposits (130-131 seismic profile interpretation in Appendix IV). This seismic record confirms the high continuity of the postglacial transgressive aquifer from slope to inland in the Llobregat delta. In summary, evidence in the Tordera and Llobregat deltas suggests that submarine canyons facilitate seawater intrusion into well preserved transgressive aquifers. In both cases, these canyons appear to hasten intrusion along the palaeochannels.

As regards the neotectonic faults, this factor is seldom identified as a potential pathway for seawater intrusion (Edwards et al., 2002; Mukherjee et al., 2005). However, we believe that it is necessary to consider seawater offshore studies in the future. Transgressive beach rock and fault scarp outcrops have been identified on the Llobregat northeastern shelf using seismic profiles and detailed relief images of the sea-floor (Liquete et al., 2007). It is reasonable to assume that the eastern sea water intrusion zone to the north of the Besòs delta is associated with a neotectonic scarp on the shelf (fig. 4.11).

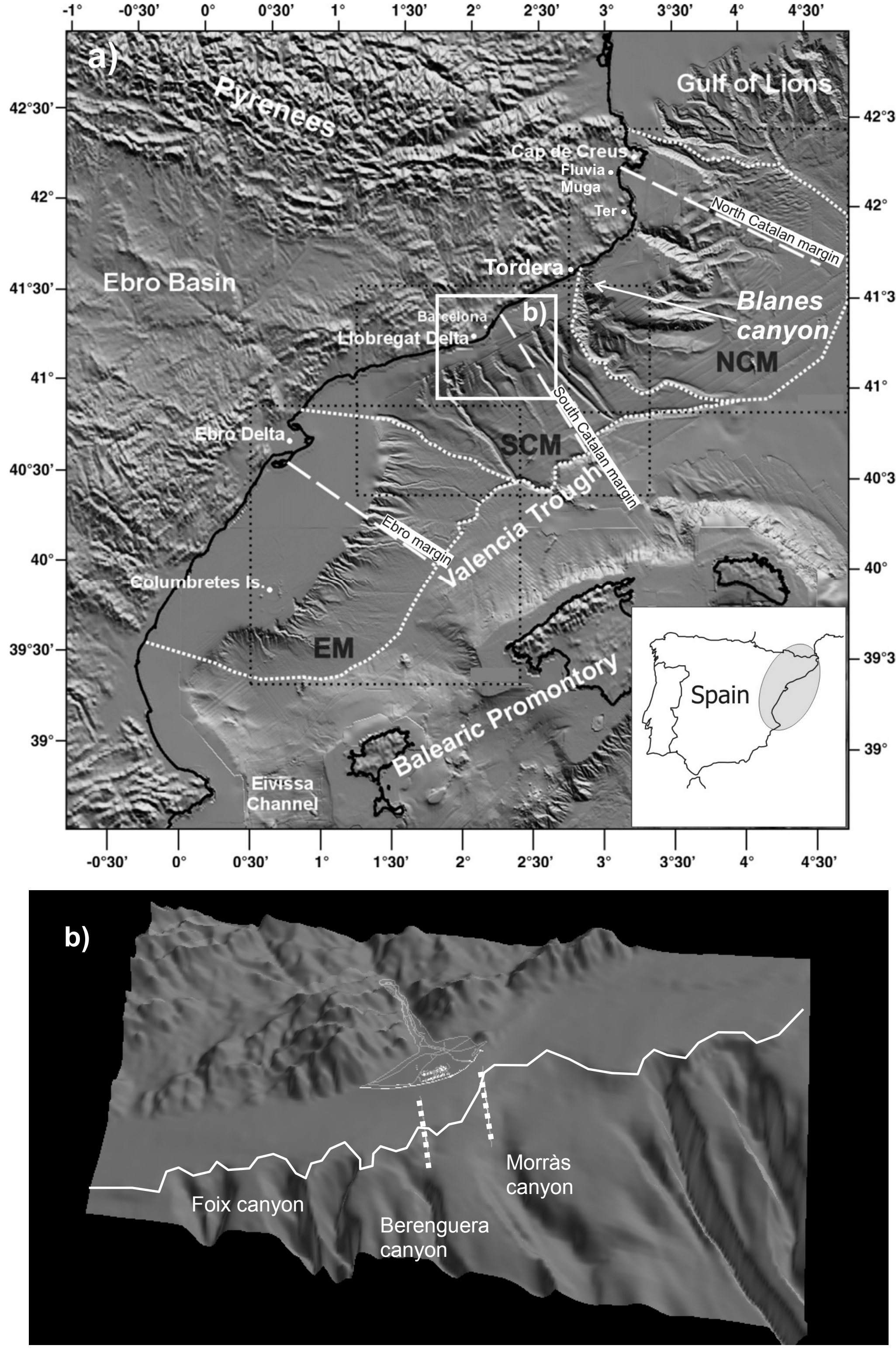

Figure 4.13: **a)** Shaded relief image of the northeast Iberian margin, with the Catalan alluvial systems mentioned in the text. The continental margin is characterized by the presence of submarine canyons that are deeply incised into the continental shelf and slope such as the Blanes canyon, which is a potential pathway for sea water intrusion into the Tordera delta. Modified from Amblas et al., 2006. **b)** Detail of the Llobregat topography and bathymetry area. We identified the submarine canyon discussed in the text. Morràs canyon is regarded as a high area that is vulnerable to seawater intrusion. Dashed line represents the seismic profile shown in figure 4.10 (south) and 4.11 (north). Solid line represents the shelf-break trace.

4.3. Conclusions

Integrating onshore and offshore geological data using sequence stratigraphy methods provides stratigraphic patterns of Quaternary delta deposits. Comparison of shelves in the Western Mediterranean shows that the differences in stratigraphic patterns and the preservation of the transgressive aquifers can be ascribed to local factors. The most important factors are tectonic uplift and sediment supply during sea level rise.

Trangressive aquifers are the most important deltaic aquifers inland. Seawater intrusion into these aquifers was delayed when these aquifers were not preserved offshore. They were preserved at sites where the continental margin was affected by subsidence and by considerable sediment supply during the sea level rise. Under these conditions, transgressive aquifers display high continuity. The Llobregat delta aquifers can be regarded as paradigmatic of this situation. Yet, onshore-offshore continuity is not a sufficient condition for a good connection to the sea. Transgressive aquifers are protected by low permeability prodelta deposits. This protection is lost because of a reduced prodelta thickness, a submarine canyon close to the shoreline or because of neotectonic faults. These factors increase the vulnerability to seawater intrusion. Faults also play a role in the disconnection of transgressive aquifers.

In addition to the connection of the transgressive aquifers to the sea under pumping conditions, the aquifers may also be salinized under natural conditions (i.e. prior to pumping). This situation arises if the average head at the aquifer divide point (where the deep aquifer connects the shallow aquifer) is low.

In short, local geological factors control seawater intrusion under natural conditions and under pumping conditions. The transgressive aquifer structure may intensify or delay seawater penetration in aquifers pumped along the coast. An improved understanding of the onshore and offshore coastal architecture would help us to estimate the impact of seawater intrusion and to implement corrective measures.