Geodynamical framework and hydrocarbon plays of a salt giant: the North Western Mediterranean Basin

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Abstract

The North Western Mediterranean Basin developed during the Oligocene-Miocene rifting of the Eastern Iberian-European magma-poor continental margin. The margin developed as a result of back-arc extension associated with the roll-back of the retreating Calabrian-Tethys subduction zone. Reinterpretation of 2D regional seismic reflection data suggests that rifting took place by hyperextension of the Iberian-European lithosphere. This process led to the seaward arrangement of distinct crustal domains, namely proximal, necking and distal, whose distribution has been partly controlled by the presence of transfer faults accommodating different amounts of back-arc extension. **The late post-rift Messinian Salinity Crisis (MSC) gave place to significant margin erosion and canyon incision whose lowstand sedimentary by-products were largely deposited prior to the Messinian evaporitic sequences.** Mesozoic-Cenozoic and Messinian to recent salt tectonics events have been recognized. Such new understanding yields a distinct regional hydrocarbon play concept for continental shelf to deep waters, including pre-salt, Messinian and post-salt plays.

Key words: *North Western Mediterranean Basin; Messinian Salinity Crisis; Crustal hyperextension; Hydrocarbon plays.*

The North Western Mediterranean Basin is located between the Iberian-European continental margin and its conjugate Corsica-Sardinia margin. It comprises the Valencia Trough and the Balearic Promontory to the SW, and the Gulf of Lion and the Provençal Oligocene-Miocene basins to the NE (Fig. 1). **The studied area displays a well-developed shelf to slope and deep basin physiography with water depths in excess of 2.5 km. Major shelf to slope depositional complexes are associated with the Ebro and Rhone Rivers (Nelson & Maldonado, 1990; Evans & Arche, 2002; Lofi *et al.,* 2003; Rabineau *et al.* 2014). The abyssal plain follows a NE-SW trending bathymetric low that corresponds to the axis of the Provençal and Algerian basins.** The Oligocene to Quaternary sedimentary infill ranges in thickness from 2 to more than 6 km (Roca, 2001). **The North Western Mediterranean Basin is characterised** by thin lithosphere ranging from 60 km beneath the Valencia Trough axis to 30 km in the Provençal basin (Roca, 2001; Roca *et al.* 2004). **The regional pattern of gravity and geoid anomalies suggest an asymmetric lithospheric thinning across the Valencia Trough and towards the Provençal Basin (Ayala *et al.* 1996, 2015). As to heat flow, data are sparse and unevenly distributed (see Roca *et al.* 2001 and Ayala *et al.* 2015 for a review), but existing surveys indicate a decrease from 88 mWm^{-2} at the SW termination of the Valencia Trough to 66 mWm^{-2} in the NE at the transition to the Provençal Basin, coincident with the deepest bathymetry and thinnest crust (Foucher *et al.* 1992, Ayala *et al.* 2015). In the central part of the Provençal Basin heat flow values seem to vary between 80-120 mWm^{-2} in the southeast and 60-85 mWm^{-2} in the northwest, with the highest values occurring in the central parts of the basin (Pasquale *et al.* 1994).**

Lithospheric thinning occurred in a continental crust that was formerly consolidated during the Variscan orogeny. During the Mesozoic opening of the Atlantic-Alpine Tethys oceans and the Bay of Biscay-Pyrenean rift, several intracontinental extensional basins like the Columbretes, Maestrat and Cameros basins developed in the Iberian Plate (Salas *et al.* 2001). During the Late Cretaceous-Cenozoic shortening these Late Jurassic-Early Cretaceous extensional basins were inverted and incorporated into the Alpine orogenic systems. Offshore in the Valencia Trough, the Alpine shortening and related uplift is evidenced by a large erosional truncation at the base of the Oligocene-Miocene sequence. It is commonly accepted that the North **Western** Mediterranean Basin formed as a back-arc basin in response to the roll-back of the African lithospheric slab, which was being subducted beneath the Eurasian and Iberian plates along the retreating Calabrian-Tethys subduction zone (**Réhault *et al.* 1984;** Doglioni *et al.* 1997**; Lonergan & White, 1997**; **Gueguen *et al.* 1998;** Roca *et al.* 1999; Roca, 2001; Cavazza *et al.* 2004; Schettino &

Turco, 2010; Jolivet *et al.* 2015). The northernmost part of the basin began to open during the Oligocene, whereas the Algerian Basin to the South opened during the middle Miocene (Sàbat *et al.* 1997). The main tectonic events and a synoptic stratigraphy of the North Western Mediterranean Basin are summarised in figure 2.

In our work, we have interpreted a large database of 2d regional seismic profiles from the Valencia Trough and the Provençal Basin. A selection of relevant examples is portrayed in figures 3, 4 and 5. These interpretations have been integrated with lithospheric break up concepts (Brun & Beslier, 1996; **Whitmarsh *et al.* 2001; Lavier & Manatschal, 2006; Péron-Pinvidic *et al.* 2013) with the aim to provide an updated geodynamic scenario and crustal architecture for the basin (Figs. 1). This map of distinct crustal domains provides a geodynamic framework for the Messinian Salinity Crisis (MSC), the observed salt-related structures and finally, a hydrocarbon plays analysis. We want to remark the large extension of the studied area and that the presented crustal architecture results, up to a certain point, from a conceptual extrapolation for the entire basin**.

Crustal domains of the North West Mediterranean Basin

Hyperextension at "magma-poor" continental margins occurs when the ductile part of the lithosphere is stretched to the point that its brittle parts become coupled, allowing for large shear zones to penetrate into the mantle (**Brun & Beslier, 1996**; Whitmarsh *et al.* 2001**). Stretching in such a way can lead to the exhumation of lower crustal rocks and ultimately, to the exhumation and related serpentinization of the uppermost lithospheric mantle.** Such break-up processes are responsible for the architectural organization of **magma-poor** continental margins and the seaward arrangement of distinct crustal domains, namely proximal, necking, distal and outer.

This architectural organization of crustal domains is mostly derived from studies in the Atlantic continental margins (**Whitmarsh et al. 2001; Lavier & Manatschal, 2006; Péron-Pinvidic *et al.* 2013**). **The proximal domain is characterised by fault-bound sediment wedges belonging to graben or half-graben basins associated with high angle or listric-shaped extensional fault systems. The necking domain displays a wedge shaped crustal geometry, with the upwarping of the lower crust and underlying Moho along major shear zones. The distal domain is fundamentally shown by the occurrence of a sag basin developed over hyper-extended crust and/or exhumed mantle as well as a shallow Moho. The outer domain in magma-poor margins is rather difficult to map as it is shown as a gradual transition into oceanic-type crust. At magma-rich margins, on the other hand, the presence of voluminous volcanic and igneous complexes produces substantial crustal thickening and related geophysical signatures (Péron-Pinvidic *et al.* 2013).**

From coastal Iberia to the Gulf of Lions, the western margin of the North Western Mediterranean Basin is affected by Oligocene-Miocene NE-trending horsts and grabens covered by a post-rift sedimentary wedge **(Roca, 2001).** A series of NW-SE-trending system of transfer faults accommodated back-arc extension and have been the loci of limited magma intrusion and lava extrusion from Aquitanian to Quaternary times (Maillard *et al.* 1992). The **North Balearic Fracture Zone is one of these fault systems and** separates the Provençal Basin, Gulf of Lions and their conjugate Corsica-Sardinia margin to the **North** from the Valencia Trough, the Balearic Promontory and the Algerian Basin to the **South** (Fig. 1b). Volcanic edifices and lava flows of Miocene calc-alkaline and Pliocene alkaline affinity have been recognised on seismic data and have also been drilled by several ODP/DSDP expeditions (Martí *et al.* 1992; Roca, 2001; Lofi *et al.* 2011a,b).

The Gulf of Lions is located on normal to slightly thinned crust belonging to the proximal domain, whereas the Provençal Basin is characterised by a thick, mostly Miocene to Plio-Quaternary sag basin that wedges out toward the Gulf of Lions and the Balearic Promontory (Figs. 3 and 4). As first pointed out by Pascal *et al.* (1992), the seismic velocities of the Provençal sag basin basement are arranged in distinct domains neither typical of continental nor oceanic crust. Their respective velocities are more consistent with lower continental crust, serpentinised lithospheric mantle (Pascal *et al.* 1993; Bache *et al.* 2010; Jolivet *et al.* 2015) and maybe, with an atypical thin oceanic crust affinity (Moulin *et al.* 2015). The transition zone between the Gulf of Lions and the Provençal Basin has been preliminary established based on the presence of lithospheric-scale shear zones (i.e., expressed as the T and R crustal reflectors of Séranne *et al.* 1995), the significant thinning of the crust away from the continent as well as the anomalous seismic velocity field (Pascal *et al.* 1993; Gorini *et al.* 1993; Séranne *et al.* 1995; Bache *et al.* 2010; Moulin *et al.* 2015). The transition from the proximal Gulf of Lions into the distal domain corresponds to the necking domain (Figs. 1b, 3, 4).

A phase of subaerial erosion related with rift margin uplift has been reported in the proximal and necking domains (Bache *et al.* 2010) and even in the distal parts of the margin (Jolivet *et al.* 2015). This long-wavelength subaerial erosion could relate to generalised rifting that initiated in Europe during the latest Eocene and protracted during the Oligocene. The presence of thick fault-bounded sediment wedges on the Provençal sag basin basement indicates graben and/or half-graben basins developed on exhumed lower continental crust (Figs. 3). Based on well (i.e., Golfe du Lion Profond 2 well – GLP2 – Guennoc *et al.* 2000) and seismic data correlation, Jolivet *et al.* (2015) have recently proposed that these

sediment wedges could be as early as late Eocene in age. Jolivet *et al.* (2015) argue that the seismic basement of the Provençal sag basin has been covered with Eocene-Oligocene extensional wedges deposited onto exhumed lower continental crust (i.e., syn-rift deposits) and lower Miocene wedges on exhumed lithospheric mantle further outboard (i.e., syn-break up deposits). Strong uncertainties remain regarding the age of these deposits as well as and their lateral correlation from the proximal to the distal settings. It needs to be pointed out that the presence of these distal rift to break-up basins is not clearly revealed by seismic data in all parts of the studied area (compare Figs. 3 and 4). On the other hand, evidences of basement extensional fault activity and volcanism in the necking domain during the middle to late Miocene are present. As shown by seismic data, these major faults and volcanic edifices may have controlled the subsequent distribution of evaporite units during the Messinian Salinity Crisis (Fig. 4). All these observations indicate the complexity of lithospheric break-up, but still suggest that it may have been a diachronic process along the continental margin. This implies that break-up sedimentation at the distal domain could have taken place in continental to marine conditions.

The distribution of crustal domains is more complex to the SW of the North Balearic Fracture Zone separating the Provençal Basin from the Balearic Promontory (Fig. 1b): seismic reflection data indicates a thick Iberian lower crust, whereas the whole extent of the Valencia Trough and the Balearic Promontory is underlain by significantly-thinned lower crust (Sàbat *et al.* 1997; Roca, 2001; Ayala *et al.* 2015). Along the axis of the Valencia Trough, the Moho rises gradually from 18-19 km at the SW end to just 8-10 km at the NE in the transition to the Provençal Basin (Ayala *et al.* 2015). **The axis of the Valencia Trough can be considered a necking**

zone with extremely thinned lower crust and a coupled upper crust and upper lithospheric mantle. Toward the SW termination of the trough, the Miocene sedimentary fill was deposited on thinned Variscan continental crust overlaid by the **6-8 km thick Late Jurassic-Early Cretaceous Columbretes Basin (Fig. 5).** It is below this Mesozoic basin that the upper crustal shear zones cross trough the reflective lower crust into the underlying lithospheric mantle **(Fig. 5). Crustal thickening associated to the Betic fold-and-thrust belt development in the Balearic Promontory took place coevally and after the main Oligocene to Miocene back-arc extensional stage, but only affected the uppermost parts of the continental crust. In this sense, this shortening has not restored the promontory's crust to its original pre-rifting thickness as the lower crust was not involved** (Sàbat *et al.* 1997; Roca, 2001). **According to the above, the Balearic Promontory represents a crustal boudin (Doglioni *et al.* 1997) or an H-Block (Peron-Pinvidic & Manatschal, 2010) between the Valencia Trough necking zone and the distal domain represented by the Algerian Basin (Fig. 1b).**

Sequence stratigraphy of the Messinian Salinity Crisis (MSC)

From a seismic point of view 4 units have been traditionally ascribed to the Messinian Salinity Crisis (see Lofi *et al.* 2011a,b; Bache *et al.* 2015 for recent reviews): a lower unit corresponding to the Lower Evaporites, an intermediate unit represented by the Mobile Unit (i.e., the megahalite body), and an upper unit corresponding to the Upper Evaporites. At the base of the slope, a chaotic and poorly imaged sedimentary body has also been recognized (Fig. 6) and mainly interpreted as clastic deposits sourced from the margin. The Lower Evaporites and Clastic Units have been grouped into a Messinian Lower Megasequence, whereas

the Mobile Unit and Upper Evaporites have been grouped into a Messinian Upper Megasequence (Gorini *et al.* 2015).

Based on our observations and previously published works (Lofi *et al.* 2011b; Bache *et al.* 2015; Gorini *et al.* 2015; Urgeles *et al.* 2011; Granado *et al.* 2015; Cameselle & Urgeles 2016) we have addressed the MSC using a simple sequence stratigraphic approach (Fig. 5) following the nomenclature provided by Haq *et al.* (1987) and Posamentier *et al.* (1988). Before the MSC, a Tortonian-age highstand systems tract (HST 1) is represented by prograding deltaic systems (Figs. 2, 6a). The HST 1 is topped by a correlative conformity (*sensu* Posamentier & Allen, 1999) that marks the sequence boundary (Fig. 6a). Then, the Messinian sealevel drawdown and its associated margin incision lead to the partial erosion of the former Tortonian deltaic system, the offlap and downlap of basinward-stepping sedimentary systems represented by slope and basin floor fans belonging to a lowstand systems tract (LST, Fig. 6b). This LST was characterized by high progradation rates, fluvial erosion and incision on the marginal exposed areas, and alluvial sedimentation on the slope and basin floor (Fig. 6b). This erosional surface is marked by a subaerial unconformity (Fig. 6b), passing toward the basin into a non-erosive maximum regressive surface. The transition point between this two time-equivalent surfaces indicates the end of the base-level fall of the shoreline. The LST deposits pass downslope and laterally into the earlier Lower Evaporites succession, and should also include the Messinian Detritals described by Lofi *et al.* (2011a,b), the U4 unit of Bache *et al.* (2015), the chaotic and imbricated units of Cameselle & Urgeles (2016) or the Messinian Clastics of Gorini *et al.* (2015). The high erosion and incision of the margin are responsible for the observed subaerial unconformity that marks locally the sequence boundary (Fig. 6b). This subaerial

unconformity should correspond to the Messinian Erosional Surface (MES) described by many authors onshore and on the Mediterranean continental shelves offshore (see Rouchy & Carusso, 2006; CIESM, 2008; Ryan, 2009; Urgeles *et al.* 2011). However, an intense debate surrounds the origin of this unconformity. Some authors postulate that the unconformity corresponds to sea-level still-stands (Lofi *et al.* 2005), while others show evidence of a genesis of this surface during falling sea level (Urgeles *et al.* 2011), and others argue that the latter stages of formation where shaped during sea-level rise (Bache *et al.* 2009, 2012, 2015; García *et al.* 2011). Extremely good preservation of fluvial deposits above the MES implies that this erosional surface developed during sea level drawdown (Urgeles *et al.* 2011; Cameselle *et al.* 2014).

Because the latest stage of reflooding of the basin has been estimated to occur in a very short time span - some authors estimate that 90% of such reflooding occurred in just 2 years (Garcia-Castellanos *et al.* 2009) - there is very little to no evidence of a Pliocene transgressive systems tract. The retrogradational and transgressive deposits, if at all present, are very thin in the Valencia Trough (Cameselle & Urgeles 2016). Nevertheless, the onlap configuration of a large part of the Lower Evaporites, the Mobile Unit and the Upper Evaporites in the Provençal basin has been interpreted to result from initial slow Messinian transgression (Bache *et al.* 2015). This transgressive systems tract (TST, Fig. 6c) was likely characterized by continued, but reduced, clastic deposition. These conditions gave way to the deposition of the later Lower Evaporites, the Mobile Unit and the Upper Evaporites in a clearly transgressive context characterized by the onlapping geometry of these units on to the early Messinian margin (Figs. 3, 4, 6c and 7a). Considerable controversy exists regarding the timing of deposition of

the Mobile Unit (i.e., the megahalite body) and the Messinian Detritals. According to Ryan (2009, 2011), salt deposition occurred early during the initial drawdown and the formation of marginal and perched gypsum basins. Other authors like Bache *et al.* (2009, 2015), Gorini et al. (2015) and Jolivet *et al.* (2015) assume that the megahalite body was deposited later, more in agreement with our scenario proposed above. In terms of relative age, this can be qualitatively assessed from seismic profiles (Figs. 3 and 4), although poor seismic resolution hampers accurate age estimation. We infer that the Messinian Clastic Units grade into the earliest Lower Evaporites, although the latter are considered to be largely clastic in origin too (Gorini *et al.* 2015). Precipitation of the late Lower Evaporites, the Mobile Unit and the Upper Evaporites took place afterwards and more importantly, without significant clastic sedimentation. In fact, the distribution of the Messinian evaporitic units seems to have been controlled, at least to a certain degree, by the inherited basement structure of the margin and volcanic edifices (Figs. 3 and 4).

Along the margin, the progradations belonging to the Plio-Quaternary HST (i.e., HST 2, Figs. 2, 6d) of the Ebro and Rhone deltas directly downlap on the Messinian Erosional Surface, whereas in the distal parts the Messininan evaporites are overlain by biogenic oozes first and then by the distal deep water turbiditic systems, roughly at the Plio-Quaternary transition (Cita, 1973; Bertoni & Cartwright, 2005; Lofi *et al.* 2005; Kertznus & Kneller, 2009; Urgeles *et al.* 2011; Rabineau *et al.* 2014). The maximum flooding surface between the top of the TST succession and the base of the HST 2 deposits is located in the base of the biogenic oozes, interpreted as a marine pelagic sedimentary unit deposited during the maximum transgression (Fig. 6d).

Salt tectonics in the North Western Mediterranean Basin

Salt tectonics in the North Western Mediterranean Basin is associated with two salt-bearing units located in different sectors: the late Triassic salts in the the Columbretes Basin within the Valencia Trough (Fig. 2) and the Messinian megahalite body in the Provençal Basin (Figs. 3, 4, 7). Well data in the Valencia Trough indicate the Late Jurassic-Early Cretaceous Columbretes Basin is characterised by a complete Mesozoic succession spanning from Triassic to Late Cretaceous times (Lanaja, 1987) **with Late Triassic salt-bearing successions** (Fig. 2). As proven onshore and offshore Iberia, the origin of the observed salt structures is related with the Late Jurassic-Early Cretaceous rifting and their subsequent deformation during Alpine shortening (Alves *et al.* 2003; Lopes *et al.* 2006; Ferrer *et al.* 2008; Roca *et al.* 2011; Mencos *et al.* 2015). In the Columbretes Basin, t**he salt-related structures are not clearly evident due to the very poor seismic imaging, but hydrocarbon exploration wells (Valencia 3-1 and Cabriel B-2A wells; Lanaja, 1987) drilled through Triassic evaporites associated with structural highs bounding major Mesozoic depocenters. The salt related structures correspond to diapirs and salt walls squeezed and reactivated to different degrees (Martínez del Olmo, 1996). Across** the Valencia Trough, the Messinian deposits are restricted to gypsum, carbonates and related clastic units with no salt-bearing formations (Rouchy & Caruso, 2006; CIESM, 2008; Ryan, 2009; Lofi *et al.* 2011b; **Cameselle & Urgeles, 2016**). As a consequence, no salt tectonics related to Messinian salts developed there.

Conversely, salt tectonics in the Provençal Basin is exclusively related to the Messinian megahalite, which corresponds to the intermediate mobile unit originally described by Montadert *et al.* (1978). Salt tectonics in the Provençal Basin is represented by a well-developed gravity-driven system (Rowan *et al.* 2004). As other world examples of gravity tectonics on continental margins salt basins, the Provençal Basin system **(Figs. 3, 4 and 7)** is arranged in distinct salt-related domains: an updip extensional belt, a translational belt and a down dip shortening belt (Dos Reis *et al.* 2008). The extensional belt **(Fig. 7a)** is characterised by regional listric faults and associated hanging wall rollovers and footwall rollers (Sans & Sàbat, 1993); this system is restricted updip by the stratigraphic pinch-out of the Messinian megahalite unit. The topographic expression of volcanic edifices in the sag basin has affected the development of the extensional belt and gravity tectonics along the margin in general (Fig. 3). The translational domain is characterised by tabular salt, but it is not present all across the basin; the shortening domain is constituted by buckle folds **(Fig. 4, 7b),** diapirs and related salt structures **(Fig. 4, 7c). The distal salt structures show flanking halokinetic sequences evidencing passive down building triggered by the Pliocene to Quaternary Rhone deep sea fan systems sedimentation. As shown by the halokinetic sequences, salt evacuation started as early as Messinian times continuing today. Halokinetic sequence patterns suggest updip migration of deformation as well, also indicated by the local absence of the tabular salt domain (Fig. 3). Some diapiric structures show primary welds even if these diapirs pierce or fold the sea bed. This is a clear indication that these structures are active, and that either salt evacuation is still ongoing, and/or downdip shortening is taken place (Fig. 7c).**

Although still a question of debate in the studied area, the most accepted mechanism for salt tectonics on continental margins is that gliding, spreading, or both, take place in relation to the regional slope that post-rift differential thermal subsidence generates. An interesting discussion on this matter has been provided

by Rowan *et al.* (2004), Brun & Fort (2011, 2012), Rowan *et al.* (2012) and more recently by Peel (2014). Sediment inputs from the continent (i.e., deltaic and deep water) and subsidence can account for differential sedimentary loading, as an additional but fundamental control for salt evacuation and inflation. In the Provençal Basin, salt tectonics most probably resulted from a combination of gliding and spreading and the downslope interaction with basement fracture zones (Maillard *et al.* 2003; Dos Reis *et al.* 2008). The studied area is particularly different to other salt giants like the Gulf of Mexico or the Central-South Atlantic margins, where the salt units were deposited either during the syn-rift or the early stages of post-rift. In the Provençal Basin, the Messinian Salt was regionally deposited within an already well-established post-rift stage and, more importantly, in a basin where no typical oceanic crust has been formed. Hence, there is no Messinian salt deposited onto the basement/oceanic crust/exhumed mantle or subsequently emplaced onto it.These differences have a strong impact on the subsequent halokinetic history and structural styles developed. A regionally deposited post-rift salt allows for a regional detachment surface along which post-rift units can glide downslope, whereas the syn-rift half-graben restricted salts form discontinuous horizons that hamper the gliding and rafting processes.

Different models to explain the observed large and delayed subsidence of the Provençal sag basin have been proposed, including that of Réhault *et al.* (1984), Séranne et al. (1999), and most recently Rabineau *et al.* (2014). According to several authors (Bache *et al.* 2009, 2012; Ryan, 2011) the MSC sealevel drawdown must have induced a large isostatic rebound of the rims of the North Western Mediterranean Basin. This rebound was followed by significant but unevenly distributed tilting and subsidence along the continental margin during the fast

Zanclean reflooding (Rabineau *et al.* 2014). Govers *et al.* (2009) and Ryan (2011) also propose that the loading imposed by the thick Messinian evaporites might have contributed to the differential subsidence and tilting, triggering salt tectonics in the Provençal Basin. According to Rabineau *et al.* (2014), the Plio-Quaternary tilting of the margin and related basin subsidence is spatially arranged in a series of distinct domains that we here assign to the proximal, necking and distal crustal domains previously described (Fig. 1b). The updip extensional belt is spatially coincident with the necking domain between the Gulf of Lions shelf and the continental rise of the Provençal Basin. The necking domain displays a regional slope into the deep sag basin that allowed for a potential energy differential that triggered salt tectonics (Rowan et al. 2004; Hudec & Jackson, 2007; Brun & Fort, 2012; Peel, 2014). The translational and shortening domains are coincident with the thickest part of the post-rift sag basin which developed on exhumed lower continental crust, whereas the distalmost domain of diapirs is coincident with the location of exhumed lower crust, serpentinised lithospheric mantle or atypical oceanic crust.

Proven and speculative hydrocarbon plays

Plays in the North Western Mediterranean Basin fall into two principal categories: proven and speculative. In this work, shallow water vs. deep water and pre-salt, Messinian and post-salt classification is proposed. Play types are summarized in Table 1 and their location is schematically represented in a play concept diagram **(Fig. 8)**. The sequential stratigraphic framework used corresponds to that presented here **(Fig. 6)** and is based on the pioneering work of Clavell & Berastegui (1991). The proven oil-prone plays of the Valencia Trough (play 2, Table 1, **Fig. 8)** are preserved on palaeohighs and tilted fault blocks (Clavell & Berastegui, 1991; Varela *et al.* 2005) on the proximal domain. Main reservoir type is constituted by Aquitanian syn-rift resedimented, fractured, karstified **and** dolomitised carbonate breccias and conglomerates of various ages. These units are overlying the Mesozoic basement, which is also fractured and karstified, and constitutes another reservoir type of less importance (M. Esteban, pers. com. 2015). Hydrocarbon migration took place from the Jurassic Ascla del Maestrat Formation and the Miocene Casablanca Shales (Fig. 2) updip and across the extensional fault system (Clavell & Berastegui, 1991).

Speculative pre-salt plays are constituted by: Mesozoic basins on the necking and proximal domains of the margin (play 1, **Figs. 3, 4, 8** and Table 1); Oligocene to Miocene continental to marine wedges on the necking and distal domains of the sag basin on top of significantly thinned crust and serpentinised mantle (play 3, Table 1, Figs. 3, 8); Tortonian deltaic sandstones (play 4) and Tortonian deep sea fans (play 5) belonging to the HST 1 (Figs. 3, **8** and Table 1). Messinian plays are constituted by: slope and basin floor fans and mass transport deposits belonging to the **LST** (plays 6 and 7, **Figs. 6b, 8**; and Table 1) presently located in deep waters; fluvial sandstones infilling the Messininan Erosional Surface (play 8) belonging to the **LST** in shallow waters (Figs. 3, **6b and** Table 1). Post-salt plays are represented by: Pliocene-Quaternary deltaic and shoreface sandstones (play 9) belonging to the HST 2 (Figs. 3, 4, **6d**, **8** and Table 1), probably charged with biogenic gas; Pliocene-Quaternary deep water turbiditic sandstones belonging to the HST 2 trapped in rollovers of the gravity-driven extensional domain (play 10, Figs. 3, **7a, 8** and Table 1), in channel/levee systems (play 11, Figs. 3, 8 and Table 1) and in halokinetic sequences related with diapirs and buckle folds of the gravity-driven shortening domain (play 12, Figs. 3, **7b,c,**

8 and Table 1); pre- to syn-kinematic carbonates of the **Upper Evaporites** (play 13, Figs. 3, **8** and Table 1)**.**

Conclusions

The North Western Mediterranean Basin shares certain stratigraphical and structural similarities with prolific salt basins such as the South Central Atlantic, but major differences exists regarding the timing of salt deposition as well as the absence of a well-developed oceanic crust. The conceptual evolutionary model presented in this manuscript provides a geodynamic-architectural framework for hydrocarbon exploration and has allowed defining a regional hydrocarbon play concept diagram, where proven and speculative plays are summarized. **The MSC had a profound effect on the Mediterranean margins' evolution in terms of subsidence, burial, isostatic rebound and salt tectonics. The architectural organization of the basin may have also controlled the distribution of the Messinian units, which overall display a regionally transgressive character.** The effects of the MSC **has provided** several potential source, reservoirs and seal horizons, in both shallow and deep waters. In particular, the **LST** sedimentary bodies and erosional features constituted multiple **reservoirs types and** stratigraphic and palaeogeographic traps. These are **regionally sealed by prodelta shales on the shelf or by layered evaporites sequences in the distal parts of the margin**. **Long-lived subsidence following rifting** in the distal domain suggests the presence of thick source and reservoir intervals overlying exhumed lower crust, and maybe, serpentinised lithospheric mantle. Additionally, biogenic gas accumulations could be trapped in the shallow water Pliocene deltaic systems.

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Figure list and captions

Figure 1. A) Geographical setting of the North Western Mediterranean Basin. **B)** Geological setting and onshore and offshore crustal domains of the studied area. The Valencia Trough and the Balearic Promontory are underlain by significantly thinned continental crust. **This regional map results from the integration of our interpretations of available seismic data (SPBAL, RM, SGV, BG, VALSIS and ECORS surveys) and previous works by Réhault *et al.* (1984), Pascal *et al.* (1992, 1993), Gorini *et al.* (1993), Séranne *et al.* (1995), Doglioni *et al.* (1997), Sábat *et al.* (1997), Lonergan & White (1997) Gueguen *et al.* (1998), Roca *et al.* (1999), Roca (2001), Cavazza *et al.* (2004), Bache *et al.* (2010), Ayala *et al.* (2015), Granado *et al.* (2015) and Jolivet *et al.* (2015) Moulin *et al.* (2015). All these data were conceptually extrapolated to the entire North Western Mediterranean Basin.** AB: Algerian Basin; BP: Balearic Promontory; GOL: Gulf of Lion; VT: Valencia Trough.

Figure 2. Main tectonic events and synoptic stratigraphy of the studied area. PB: Provençal Basin; VT: Valencia Trough; BP: Balearic Promontory. Based and modified from Clavell & Berastegui (1991).

Figure 3. NW-SE trending seismic section SPBAL01_16 along the Provençal Basin. Significant outboard thinning of the crust is marked by the Moho upwarping and the “T” and “R” reflections in the necking domain. Rift basins developed onto the exhumed lower crust (ELC) of the distal domain. A volcanic edifice (V) is located above the necking zone and has interacted with the gravity-driven system associated to the Messinian salt. The intracrustal reflector is taken from Moulin *et al.* (2015). PQ: Pliocene-Quaternary; UE: Upper Evaporites; MU: Mobile Unit (megahalite body); LE: Lower Evaporites; Tort: Tortonian; M Mio: middle

Miocene; Olig - L Mio: Oligocene to lower Miocene; Mz: Mesozoic Basin. UC: Upper Crust; LC: Lower Crust. See figure 1b for location of the seismic profiles.

Figure 4. NE-SW trending seismic section SPBAL01_23 along the Provençal Basin. Significant outboard thinning of the crust is marked by the "T" and "R" reflections in the necking domain. Note the significant wedging of the sag basin infill. The Lower Evaporites (LE) are clearly onlapping (see white arrow) and wedging out onto the Balearic Promontory (BP). The Mobile Unit (MU) thins out abruptly over a rift fault and a volcanic mound at the necking domain. The Upper Evaporites (UE) are the extensive most Messinian unit onlapping further to the SW onto the BP. PQ: Pliocene-Quaternary; Tort: Tortonian; V: Volcanics; Mz: Mesozoic Basin; ELC: Exhumed Lower Continental Crust. See figure 1b for location of the seismic profile.

Figure 5. WNW-ESE trending seismic section **SGV01-107** along the Valencia Trough and the Mesozoic Columbretes Basin. Note the significant thinning of the reflective lower crust and its disappearance towards the ESE below a trans-lithospheric shear zone. The strong erosion of the Mesozoic units below Oligocene to lower Miocene strata provides evidence for the Alpine shortening and uplift. Miocene sediment wedges, faulting and local uplift of this erosional surface evidences the Oligocene to Miocene rifting of the Valencia Trough and coeval shortening of the Balearic Promontory (see Fig. 2). Thin unconformable Messinian deposits are present in the trough and have been buried by the prograding and aggrading Pliocene to Quaternary delta system following post-Messinian flooding. T_R: Triassic salt diapir. **See figure 1b for location of the seismic profile.**

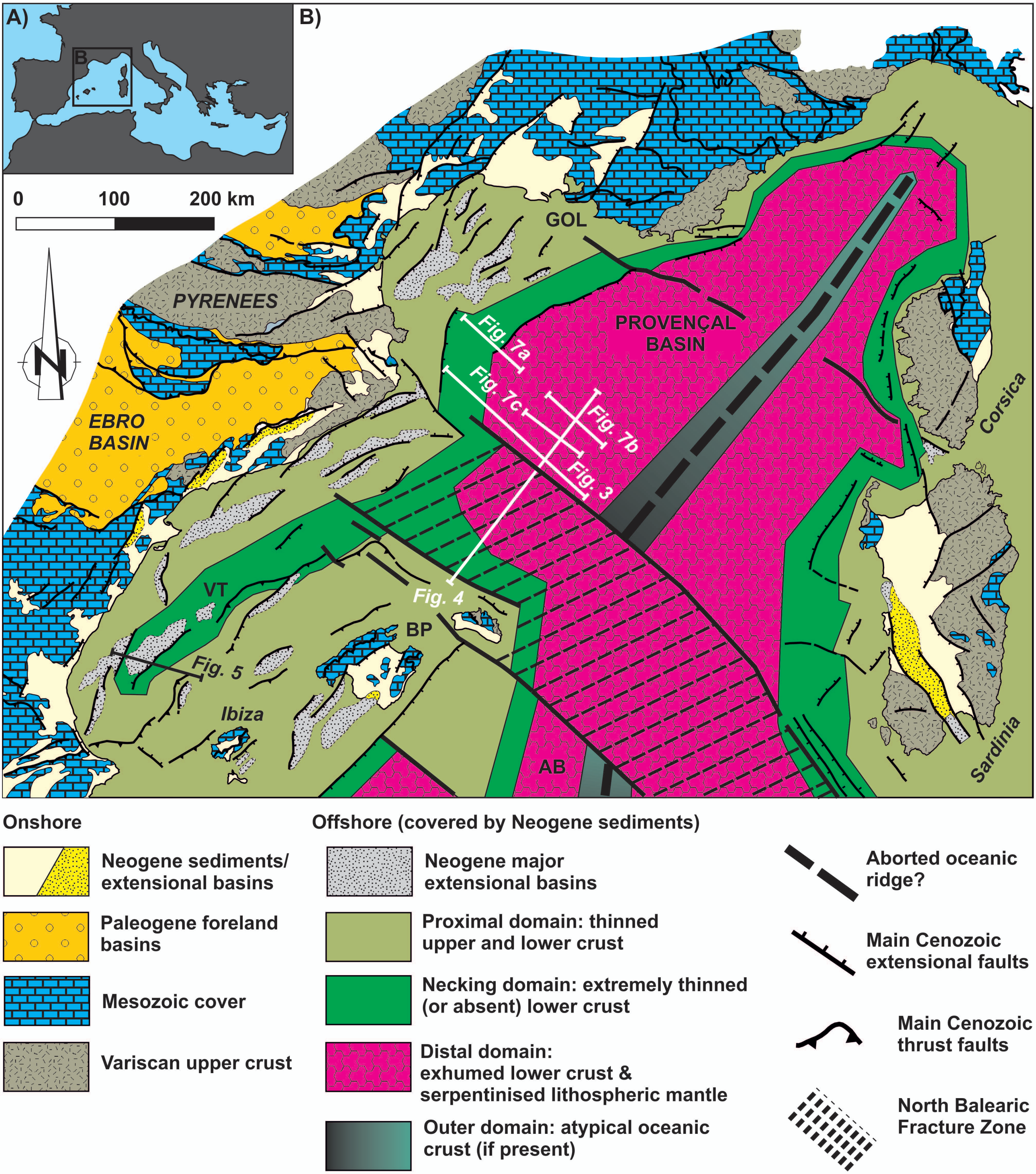
Figure 6. Sequential stratigraphy of the Messinian Salinity Crisis proposed in this study. A) Tortonian High Stand Systems Tract 1 (HST1). B) Messinian lowstand systems tract (LST). C) Messinian transgressive systems tract (TST). D) Pliocene – Quaternary High Stand Systems Track 2 (HST 2). Refer to the text for explanations. Sequential stratigraphy terms refer to those by Haq *et al.* (1987), Posamentier *et al.* (1988) and Posamentier & Allen, 1999.

Figure 7. Saline structures related with the Messinian salt (MU) in the Provençal sag basin. A) SE-directed regional listric growth faults belonging to the extensional domain of the gravity-driven system. These faults sole into the mobile unit and have associated hanging-wall rollover folds and footwall salt rollers. Note how the earlier Lower Evaporites (LE) pass laterally into the Messinian Detritals (MD), whereas the late Lower Evaporites (LE) onlap onto these deposits. The mobile salt unit thins toward the NW but it is still is on top of the Messinian Detritals. Taken from seismic profile SPBAL01-04. B) Buckle folds of the shortening domain of the gravity-driven system. Note the thickness changes of the Upper Evaporites and along the Pliocene-Quaternary (PQ) succession indicating early but continued evacuation of Messinian salt. Taken from seismic profile SPBAL01-04. C). Diapir of Messinian salt in the distal domain of the gravity-driven system. The geometries of the Pliocene-Quaternary halokinetic sequences associated to the diapir are also indicative of early salt evacuation mostly by passive down building. Although primary welds (i.e., black circles) at both sides of the diapir can be recognised, the seabed is folded, suggesting the structure is actively growing either by being sourced from outside the section or by being shortened. Taken from seismic profile RM01_214. See figure 1b for location of the seismic profiles.

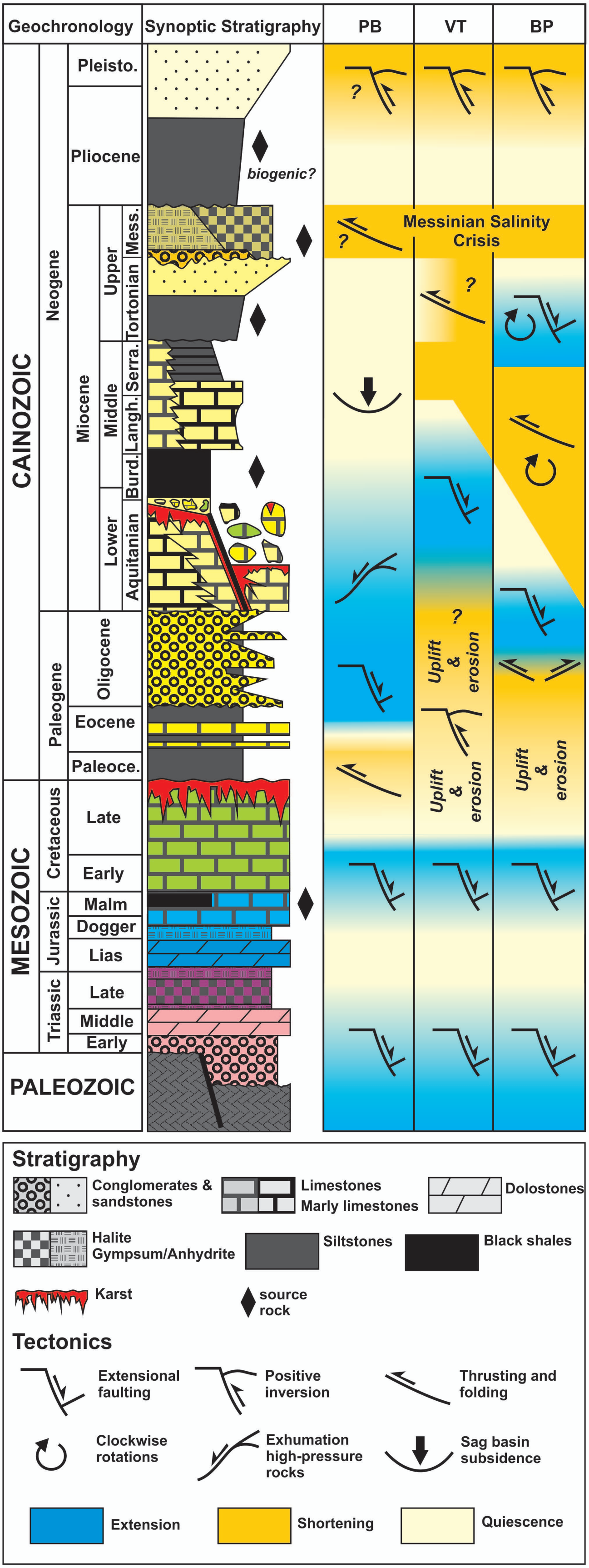
Figure 8. Play concept diagram for the North Western Mediterranean Basin. The diagram includes shallow to deep waters regions and conceptually integrates the described crustal and salt-related domains and their respective prospective areas. See text and table 1 for explanations.

Tables

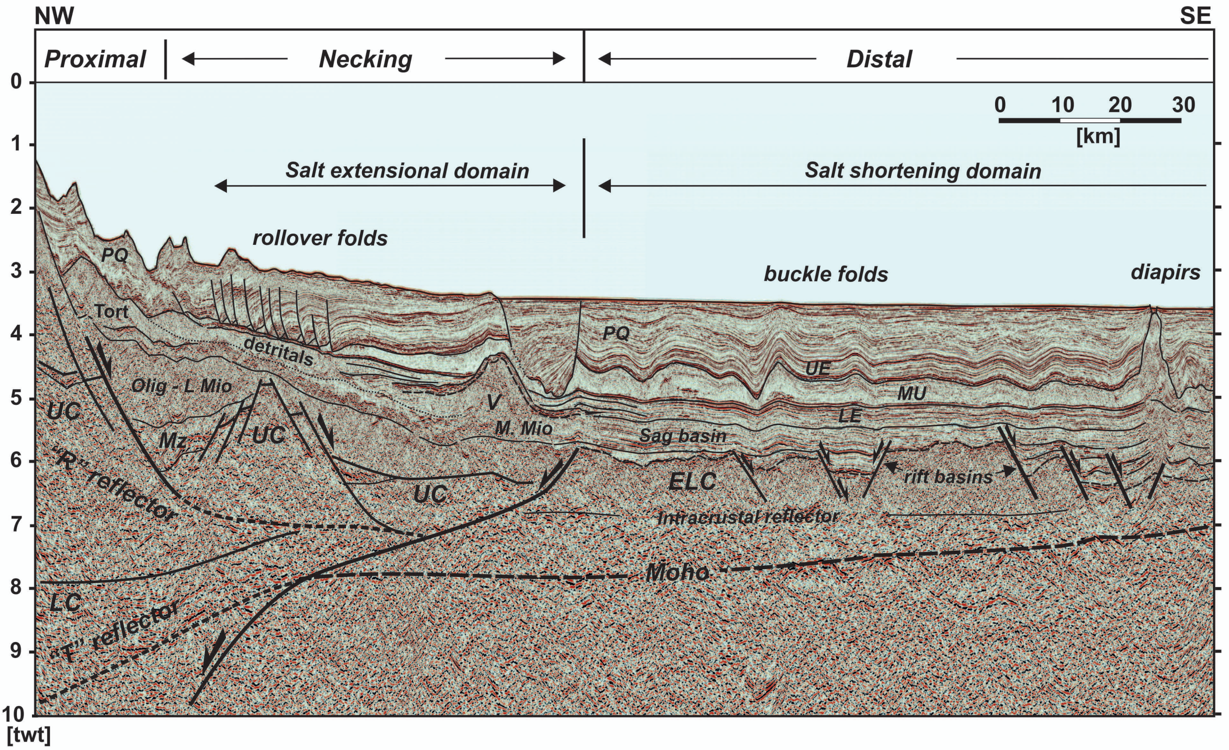
Table 1. Summary chart of North Western Mediterranean Basin plays.



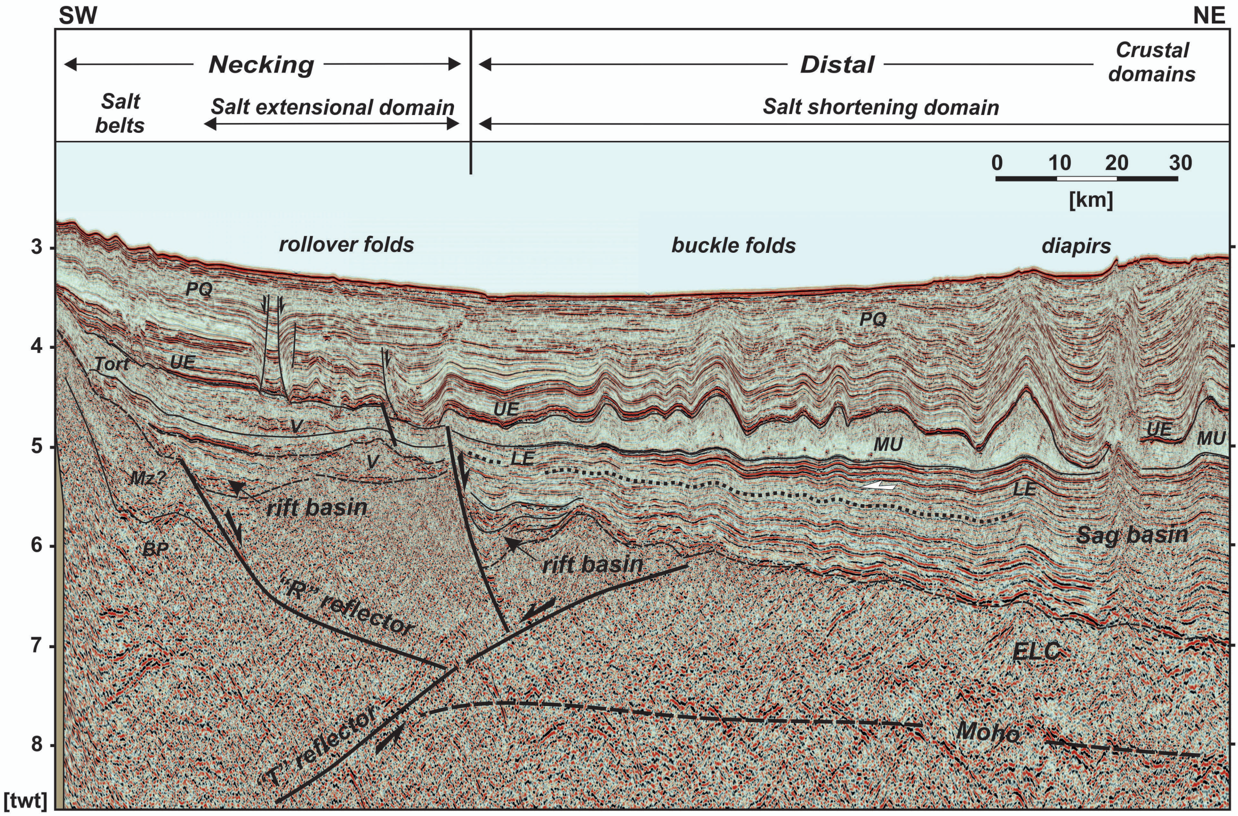
A)
B
B)
0
100
200 km
N
GOL
PYRENEES
PROVENÇAL
BASIN
EBRO
BASIN
Fig. 7a
Fig. 7c
Fig. 7b
Fig. 3
Fig. 4
Fig. 5
VT
BP
Ibiza
AB
Corsica
Sardinia
Onshore
Neogene sediments/ extensional basins
Paleogene foreland basins
Mesozoic cover
Variscan upper crust
Offshore (covered by Neogene sediments)
Neogene major extensional basins
Proximal domain: thinned upper and lower crust
Necking domain: extremely thinned (or absent) lower crust
Distal domain: exhumed lower crust & serpentinised lithospheric mantle
Outer domain: atypical oceanic crust (if present)
Aborted oceanic ridge?
Main Cenozoic extensional faults
Main Cenozoic thrust faults
North Balearic Fracture Zone

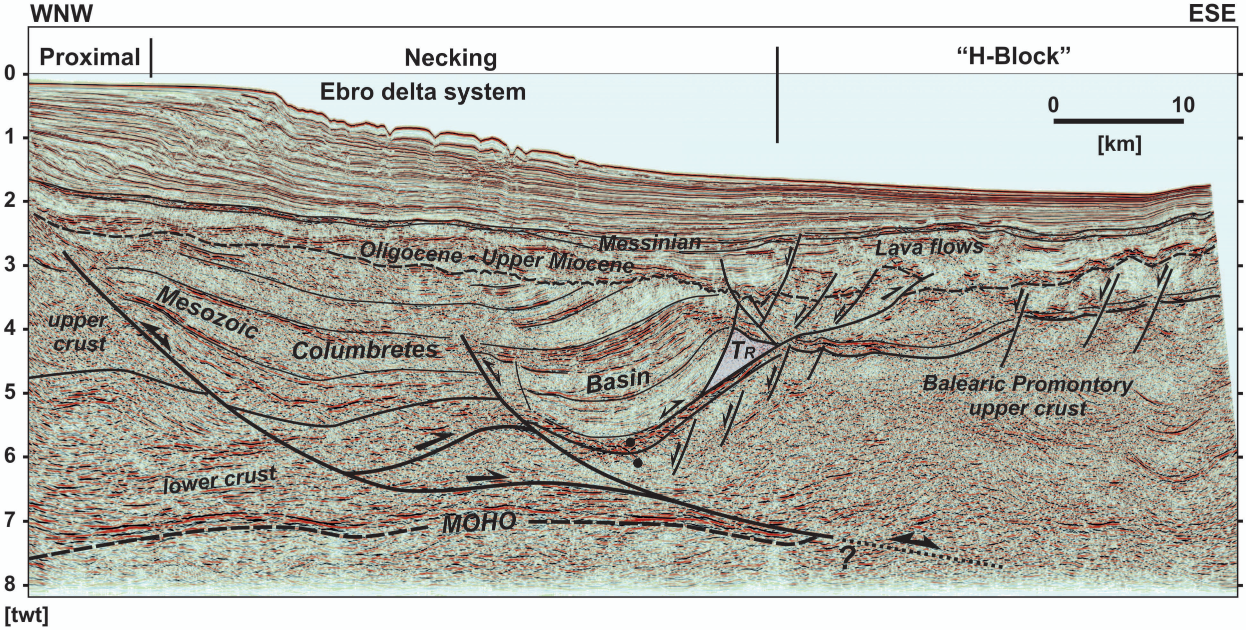


Geochronology
Synoptic Stratigraphy
PB
VT
BP
CAINOZOIC
Neogene
Pleisto.
Pliocene
Miocene
Upper
Mess.
Tortonian
Middle
Serra.
Langh.
Burd.
Lower
Aquitanian
Paleogene
Oligocene
Eocene
Paleoce.
MESOZOIC
Cretaceous
Late
Early
Jurassic
Malm
Dogger
Lias
Triassic
Late
Middle
Early
PALEOZOIC
biogenic?
Messinian Salinity Crisis
?
Uplift & erosion
Uplift & erosion
Uplift & erosion
Stratigraphy
Conglomerates & sandstones
Limestones
Marly limestones
Dolostones
Halite
Gympsum/Anhydrite
Siltstones
Black shales
Karst
source rock
Tectonics
Extensional faulting
Positive inversion
Thrusting and folding
Clockwise rotations
Exhumation high-pressure rocks
Sag basin subsidence
Extension
Shortening
Quiescence

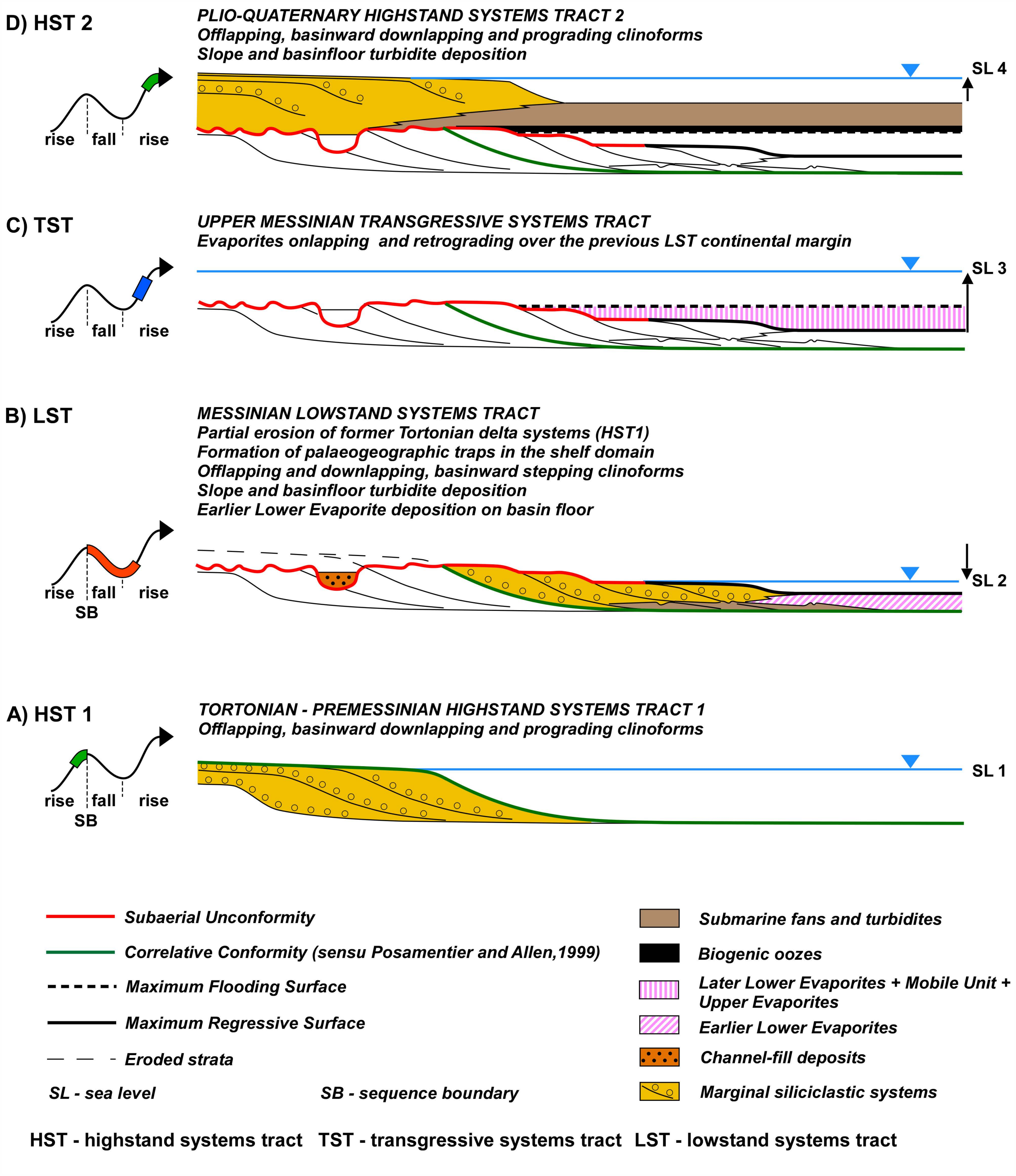


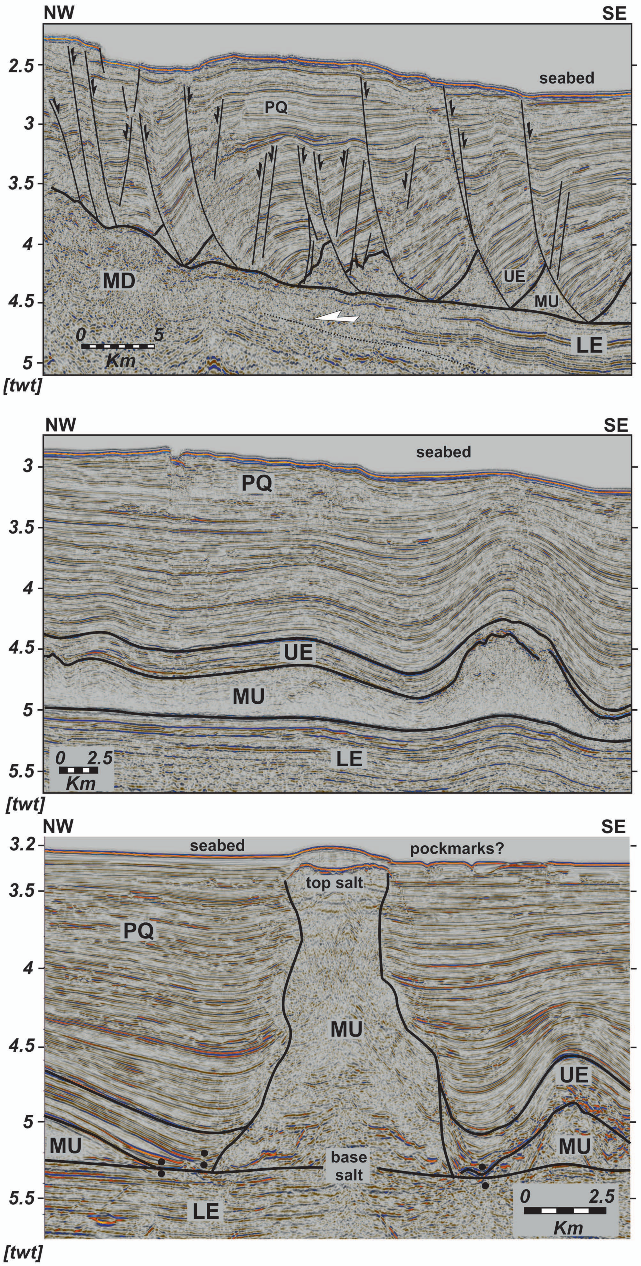
NW
SE
Proximal
Necking
Distal
0
10
20
30
[km]
Salt extensional domain
Salt shortening domain
rollover folds
buckle folds
diapirs
PQ
Tort
detritals
Olig - L Mio
UC
Mz
UC
V
M. Mio
PQ
UE
MU
LE
Sag basin
rift basins
ELC
UC
Intracrustal reflector
"R" reflector
Moho
LC
"T" reflector
0
1
2
3
4
5
6
7
8
9
10
[twt]

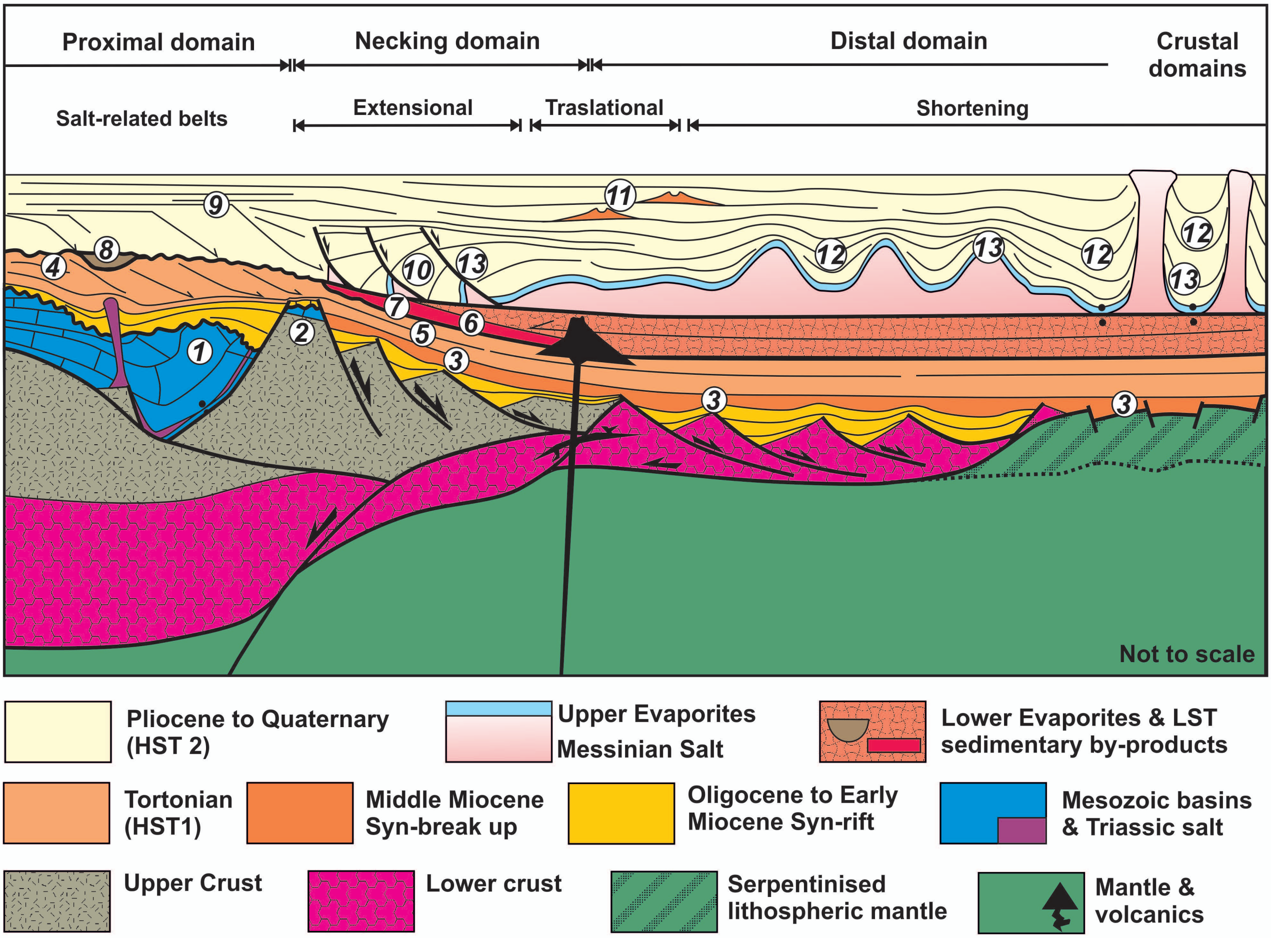

SW
NE
Necking
Distal
Crustal domains
Salt belts
Salt extensional domain
Salt shortening domain
0 10 20 30
[km]
rollover folds
buckle folds
diapirs
3
4
5
6
7
8
[twt]
PQ
Tort
UE
V
V
Mz?
BP
rift basin
rift basin
LE
MU
LE
Sag basin
"R" reflector
"T" reflector
ELC
Moho



WNW
ESE
Proximal
Necking
"H-Block"
Ebro delta system
0
10
[km]
0
1
2
3
4
5
6
7
8
[twt]
Messinian
Oligocene - Upper Miocene
Lava flows
Mesozoic
upper crust
Columbretes
Basin
TR
Balearic Promontory upper crust
lower crust
MOHO
?


D) HST 2
PLIO-QUATERNARY HIGHSTAND SYSTEMS TRACT 2
Offlapping, basinward downlapping and prograding clinoforms
Slope and basinfloor turbidite deposition
SL 4
rise
fall
rise
C) TST
UPPER MESSINIAN TRANSGRESSIVE SYSTEMS TRACT
Evaporites onlapping and retrograding over the previous LST continental margin
SL 3
rise
fall
rise
B) LST
MESSINIAN LOWSTAND SYSTEMS TRACT
Partial erosion of former Tortonian delta systems (HST1)
Formation of palaeogeographic traps in the shelf domain
Offlapping and downlapping, basinward stepping clinoforms
Slope and basinfloor turbidite deposition
Earlier Lower Evaporite deposition on basin floor
SL 2
rise
fall
rise
SB
A) HST 1
TORTONIAN - PREMESSINIAN HIGHSTAND SYSTEMS TRACT 1
Offlapping, basinward downlapping and prograding clinoforms
SL 1
rise
fall
rise
SB
Subaerial Unconformity
Correlative Conformity (sensu Posamentier and Allen,1999)
Maximum Flooding Surface
Maximum Regressive Surface
Eroded strata
SL - sea level
SB - sequence boundary
Submarine fans and turbidites
Biogenic oozes
Later Lower Evaporites + Mobile Unit + Upper Evaporites
Earlier Lower Evaporites
Channel-fill deposits
Marginal siliciclastic systems
HST - highstand systems tract
TST - transgressive systems tract
LST - lowstand systems tract


NW
SE
seabed
PQ
MD
UE
MU
LE
0 5 Km
2.5
3
3.5
4
4.5
5
[twt]
NW
SE
seabed
PQ
UE
MU
LE
0 2.5 Km
3
3.5
4
4.5
5
5.5
[twt]
NW
SE
seabed
pockmarks?
top salt
PQ
MU
UE
MU
MU
base salt
LE
0 2.5 Km
3.2
3.5
4
4.5
5
5.5
[twt]


Proximal domain
Necking domain
Distal domain
Crustal domains
Salt-related belts
Extensional
Traslational
Shortening
Not to scale
Pliocene to Quaternary (HST 2)
Upper Evaporites
Messinian Salt
Lower Evaporites & LST sedimentary by-products
Tortonian (HST1)
Middle Miocene Syn-break up
Oligocene to Early Miocene Syn-rift
Mesozoic basins & Triassic salt
Upper Crust
Lower crust
Serpentinised lithospheric mantle
Mantle & volcanics