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Salt morphologies and crustal segmentation relationship: New insights from the Western Mediterranean Sea

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ABSTRACT

Salt tectonics at salt-bearing margins is often interpreted as the combination of gravity spreading and gravity gliding, mainly driven by differential sedimentary loading and margin tilting, respectively. Nevertheless, in the Western Mediterranean Sea, the classical salt-tectonic models are incoherent with its morpho-structural setting: Messinian salt was deposited in a closed system formed several Ma before the deposition, horizontally throughout the entire deep basin, above a homogenous multi-kilometer pre-Messinian thickness. The subsidence is purely vertical in the deep basin, implying a regional constant initial salt thickness. The post-salt overburden is homogenous and the distal salt deformation occurred before the mid-lower slope normal-fault activation. Instead, the compilation of MCS and wide-angle seismic data highlighted a clear coincidence between crustal segmentation and salt morphology domains. The salt structures change morphology at the boundary between different crustal natures. Regional thermal anomalies and/or fluid escapes, associated with the exhumation phase, or mantle-heat segmentation, could therefore play a role in adding a further component to the already known salt-tectonics mechanisms. The compilation of crustal segmentation and salt morphologies in different salt-bearing margins, such as the Santos, Angolan, Gulf of Mexico and Morocco-Nova Scotia margins, seems to depict the same coincidence. In view of the evidences observed in the Western Mediterranean Sea, the influence of the temperature parameter on salt deformation should not be overlooked and warrants further investigation.

1. Introduction

The study of salt tectonics is a widely discussed topic, particularly since 1990 and mainly due to its importance in oil exploration. Under geological strain rate and due to its rheological properties, salt or halite, flows like a fluid causing spectacular geometries. Triggering can be induced by several different mechanisms, including gravity, tectonic force, salt buoyancy and differential loading (Ge et al., 1997; Hudec and Jackson, 2007). On passive margins, salt tectonics is divided into three domains (Jackson et al., 1994; Letouzey et al., 1995; Ings and Shimeld, 2006; Hudec and Jackson, 2007): an extensional zone on the slope dominated by basement-involved or basement-detached reactive diapirism and/or normal faulting (Duval et al., 1992; Jackson et al., 1994; Vendeville et al., 1995), a mid-slope more or less undeformed transitional domain (Cramez and Jackson, 2000; Dooley et al., 2013; Ge et al., 2019) and an area of contraction characterized by salt thickening, thrust faults and folding (Hudec and Jackson, 2006). Regional differential loading and sliding along a detachment surface are often summarized as the cause of gravity spreading and gravity gliding end-member models, respectively. The discussion of which of the two models prevails is still debated (Brun and Fort, 2011, 2012; Rowan et al., 2012; Schultz-Ela, 2001; Peel, 2014). During gravity spreading, salt moves by sedimentary differential loading (Ge et al., 1997; Jackson and Talbot, 1986; Vendeville, 2005; Hudec and Jackson, 2007) whilst during gravity gliding, the salt and its overburden slide towards the deep basin (Cobbold et al., 1989; Demercian et al., 1993; Fort et al., 2004) triggered by the

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inclination of the margin during thermal subsidence and/or margin uplift.

During the well-known Messinian Salinity Crisis (MSC) in the Mediterranean Sea, evaporite deposition (up to 3 km thick, Haq et al., 2020) was triggered by a combination of global tectonic events, which led to the closure of the Strait of Gibraltar (e.g. Garcia-Castellanos and Villaseñor, 2011; Leroux et al., 2019; Bulian et al., 2021) and climatic evolution (e.g. CIESM, 2008). Salt tectonics in the Western Mediterranean Sea has been studied since the works of Le Cann (1987), Gaullier (1993)) and Gorini (1993)) in the Liguro-Provençal basin, and, along with recent studies, is outlined as the combination of several parameters: (i) differential loading and gliding of the brittle-ductile series during gravity spreading (Dos Reis et al., 2005; Gaullier et al., 2008; Obone-Zue-Obame et al., 2011), (ii) initial conditions and morpho-structure evolution of the basin (Gaullier et al., 2008), (iii) a local geodynamic setting that could induce thick-skinned tectonics (Maillard et al., 2003; Déverchère et al., 2005; Dos Reis et al., 2008).

In this paper, we present a regional study of salt tectonics in the Western Mediterranean, based on a Deep/Surface approach. We analysed the relationship between salt morphologies and crustal nature in well-studied salt-bearing basins throughout the world. We first focused on the Western Mediterranean Sea (Fig. 1), for which we present a new, detailed map of salt morphologies. We categorized regional salt morphologies in order to superimpose them on the crustal segmentation, constrained by wide-angle seismic studies, magnetic and gravity maps. We then discussed the possible causes for this relationship, taking into account the specific features of the Western Mediterranean Sea. We then applied the same method to South-Atlantic margins (Angolan and Santos Basins), Gulf of Mexico, Morocco and Nova Scotia margins in order to explore the crustal-segmentation/salt-morphology relationship in different salt tectonics systems.

2. Particularity of the Western Mediterranean salt-bearing basin: a divergent closed and fossil system

2.1. Geological framework

The Cenozoic opening of the Western Mediterranean in an overall convergence context between Africa and Eurasia is closely linked to the creation of the Alpine chains, which surround it (e.g. Carminati et al., 2012). The Algero-Provençal basin opened during the Late Oligocene-Early Miocene times in the Tethyan subduction zone context. Since Late Oligocene, the slab retreat is predominant in the formation of back-arc basins, such as the Alboran, the Liguro-Provençal, the Tyrrhenian, the Aegean basins (Jolivet and Faccenna, 2000). The Liguro-Provençal basin was created by the counter-clockwise rotation of the Corso-Sardinian block (e.g. Auzende et al., 1973; Olivet, 1996), dated to Late Eocene (~Priabonian: 33.7 Ma) ranging between 23 to 19 Ma according to authors (Leroux et al., 2019). The reconstruction of the initial conditions of Liguro-Provençal rifting (Bache et al., 2010) shows similarities with those of Central (Labails et al., 2009) and South Atlantic margins (Moulin et al., 2005; Aslanian et al., 2009; Aslanian and Moulin, 2012), such as the high structural position before the breakup and the strong subsidence that followed.

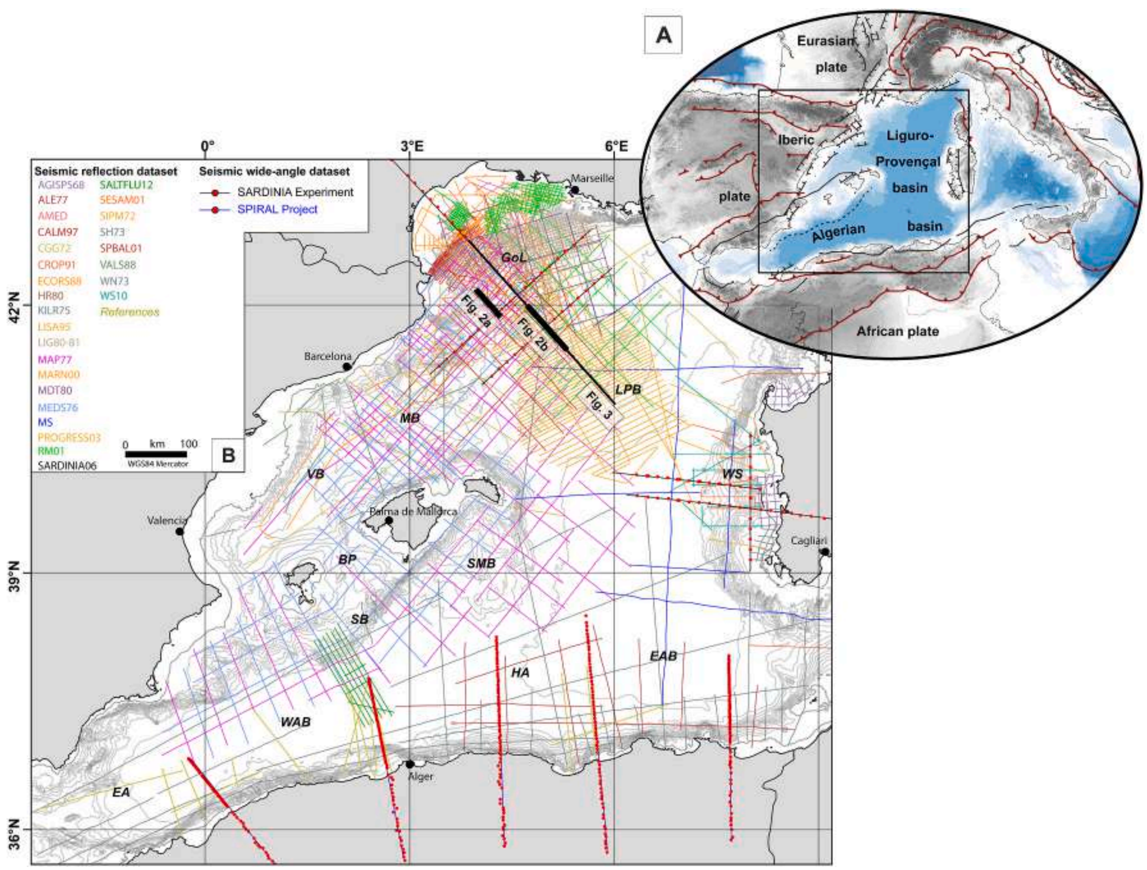


Fig. 1. A) Location of the study area marked by the black outlined rectangle. Note the structural threshold separating the Western Mediterranean Sea to the Atlantic Ocean and the Tyrrhenian basin, making it a present-day closed system. B) Dataset and bathymetry of the Western Mediterranean Sea. Bathymetric contours every 200 m. MCS and wide-angle seismic lines are represented. Red circles represent the OBS and the land stations deployed for the wide-angle acquisition. References profiles are from work of Leprêtre et al. (2013); Badji (2014); Arab et al. (2016). Labels: Gulf of Lion (GoL), LPB (Liguro-Provençal basin), WS (west Sardinian margin), MB (Minorca basin), VB (Valencia basin), EAB (east Algerian basin), HA (Hannibal area), WAB (western Algerian basin), EA (east Alboran margin), SMB (south Minorca Block), SB (south Balearic margin), BP (Balearic promontory).

While there is a general consensus on the geodynamics of the Liguro-Provençal basin, the opening direction of the Algerian basin is still a matter of debate, as well as the initial position of the AlKaPeCa (Alboran, Kabylies, Peloritan and Calabria) blocks. There are several hypotheses regarding the opening direction and nature of the margins (Leroux et al., 2019). The first group of authors claim a dominant N-S opening (e.g. Gueguen et al., 1998; Frizon de Lamotte et al., 2000; Rosenbaum et al., 2002; Schettino and Turco, 2006) with no significant displacement of the Alboran block (Faccenna et al., 2004). The second hypothesis claims an E-W opening with an important westward migration of the Alboran block (e.g. Malinverno and Ryan, 1986; Royden, 1993). The third hypothesis proposes a two-step opening scenario, with a first N-S movement, which led to the opening of the East Algerian basin and a second E-W movement, with the opening of the West Algerian basin (Etheve et al., 2016; Lepretre et al., 2018). Another model claimed by Vergés and Fernàndez (2012) proposes an initial SE-dipping subduction that shifted to a faster E-dipping subduction, which could explain some observations made for the Betic-Rif orogenic system, including the Alboran back-arc basin opening. Other authors do not agree with the rollback process and propose a collapse of the thickened continental crust (Dewey et al., 1989) or a lithospheric delamination (Roure et al., 2012).

In the Algerian basin, the Plio-Quaternary period is affected by tectonic inversion caused by the NW-SE convergence between the African and European plates with a slow rate of shortening (0.5 to ~1 cm/yr) (Kherroubi et al., 2009). This still present-day shortening causes deformation and tectonic inversion offshore Algeria (Déverchère et al., 2005; Domzig et al., 2006; Leffondré et al., 2021) and even in the SE Iberian margin (Maillard and Mauffret, 2013). The Algerian tectonic inversion is the only remarkable post-salt deposition tectonic activity that could have an impact on the present-day salt structures.

About 6 million years ago (~5.96- 5.32 Ma, Krijgsman et al., 1999), when the Algerian and Liguro-Provençal basins were already formed, the Mediterranean underwent a rapid and extreme paleo-environmental event known as the Messinian Salinity Crisis. The closure of the Strait of Gibraltar (Hsü et al., 1973), or deeper lithospheric processes (Garcia-Castellanos and Villaseñor, 2011), caused a significant sea-level fall and the deposition of evaporites associated with considerable erosion mostly located in the upper parts of the margin (e.g. Clauzon et al., 1996; Rouchy and Caruso, 2006). The salt in the Western Mediterranean was therefore deposited in a post-rift situation in contrast to most salt-bearing passive margins, where salt deposition is linked to rifting-drifting phases. The Messinian deposits have been described as a trilogy, composed of lower evaporites, salt and upper evaporites (Montadert et al., 1970; Rehault et al., 1985). The salt layer is considered to be composed of pure halite, while the evaporites can be interpreted as intercalations of gypsum/anhydrite and clastic deposits. The uppermost part of Upper Evaporites (also called Upper Unit, Lofi et al., 2011, Lofi, 2018) was sampled during DSDP Leg XIII (Hsü et al., 1973) revealing dolomitic marls and anhydrite layers. Nevertheless, the vertical and lateral facies variability suggest that the lithology of the Upper Unit can vary at the basin scale (Lofi et al., 2011). The Upper and Lower evaporites are considered less ductile than pure halite, as anhydrite creeps slower than gypsum which in turn creeps slower than halite (Jackson and Hudec, 2017). In most cases, they brittly accommodated the underlying salt deformation.

The Messinian units are deposited above a thick Miocene sedimentary sequence characterized by thickness variations between the Western Mediterranean sub-basins. The Oligocene syn-rift to Miocene post-rift sedimentary units are composed, by analogy with onshore drills (e.g. onshore Kabyle, Algeria, Géry, 1981; Onshore Camargue, France, Triat, 1983), of silty marl, conglomerates and sandstones, showing facies from shallow water to deep marine. In seismic, these deposits onlap the acoustic basement reflector and fill the pre-existing structural lows. At the present day and at basin scale, they are sub-horizontal, parallel to the base of salt and mostly unfaulted.

Salt is ductile and, in the Western Mediterranean Sea, is deposited as a flat horizontal layer above the pre-Messinian units. The base salt present-day slope surface thus indicates the post-deposition movement, mainly caused by differential subsidence or tectonic activity. In the Gulf of Lion, first Rabineau et al. (2014) with a 2D dataset and then Leroux et al. (2015) with a 3D grid calculated the subsidence up to present day using sedimentary geometries. They define three subsidence domains, from the shelf to the deep basin, which fit with the hinge lines defined by refraction studies by Moulin et al. (2015) (see chapter below) and by interpretation by Bache et al. (2010). On the platform and on the slope, they observed a seaward tilting of different amplitudes, varying from the Miocene (0.06° Ma^{-1} – 0.12° Ma^{-1}) to the Plio-Quaternary age (0.16° Ma^{-1}) (Leroux, 2012; Leroux et al., 2014). Instead, in the central deep basin, they calculated a purely vertical post-rift subsidence, with a mean rate of 500 m/Ma since 20 Ma, supposedly to be the end of rifting age (Séranne, 1999). The Gulf of Lion therefore acts as a sag basin, with some features similar to those of the Angolan margin (Moulin et al., 2005; Aslanian et al., 2009) and Santos basin (Klingelhoefer et al., 2014; Evain et al., 2015). In this work, the term "sag basin" refers to the sedimentary sequence below the salt, characterized by flatly layered sedimentation (Moulin et al., 2005; Karner and Gambôa, 2007; Bache et al., 2010) and purely vertical subsidence.

The post-Messinian series (Pliocene and Quaternary deposits) in the Algerian basin has a lower thickness than in the Liguro-Provençal (0.8 km and 2 km, respectively; from Mauffret et al., 2004), whereas it is roughly similar between the eastern and western Algerian basins and western Sardinian margins (Dal Cin et al., 2016).

2.2. *Salt tectonics mechanisms*

In the Western Mediterranean, salt tectonics has previously been locally described by some authors, for example in the Gulf of Lion (Le Cann, 1987; Pautot et al., 1984; Gaullier, 1993; Gorini, 1993; Dos Reis, 2001; Dos Reis et al., 2005; Dos Reis et al., 2008; Maillard et al., 2003; Granado et al., 2016), in the Provence margin (Obone-Zue-Obame et al., 2011), in the west Sardinian margin (Geletti et al., 2014; Dal Cin et al., 2016), in the South Balearic basin (Camerlenghi et al., 2009; Dal Cin et al., 2016; Blondel et al., 2021) and in the north Algerian margin (e.g. Déverchère et al., 2005; Domzig et al., 2006; Arab et al., 2016). Following these works, the salt structures in the Western Mediterranean Sea are mainly the result of: i) multi-directional thin-skinned tectonics driven by the seaward dipping base of salt and the sedimentary loading provided by thickness differences in the overburden, ii) the local geodynamic context which, via differences in the sub-salt setting, could influence salt deformation, as shown by several authors for several other passive margins (e.g. Haddou and Tari, 2007; Evans and Jackson, 2020; Pichel et al., 2020). The updip extension area is characterized by normal basinward-dipping faults, salt rollers and rollover strata and is considered to be coeval with thrusting and buckling in the distal contraction domain (Cobbold and Szatmari, 1991; Marton et al., 2000; Cramez and Jackson, 2000; Tari and Jabour, 2013; Brun and Fort, 2004, 2011; Rowan et al., 2004). Nevertheless, in the Gulf of Lion, the listric faults were activated only in the Early Pliocene, as evidenced by growth strata and rollover structures clearly visible above the Messinian deposits (Fig. 2a): the basinward-dipping normal faults in that proximal domain were activated only after the complete deposition of the UU, as highlighted by the constant thickness of this unit involved in the displacement. Conversely, in the deep basin, the difference in thickness and the onlaps in the Upper Unit (UU) (Fig. 2b) suggest a salt deformation that began with the deposition of this unit, still belonging to the Messinian Salinity Crisis (Gaullier et al., 2012): the sliding postdates the deep deformation. It seems that early vertical deformation in the deep basin cleared the space to allow salt gliding from the lower slope, leading to listric fault formation.

Some authors (Le Cann, 1987; Pautot et al., 1984; Maillard et al., 2003) observed a striking correlation between the OCT (Ocean-Continent Transition) limit and a variation in salt structures in the Gulf of

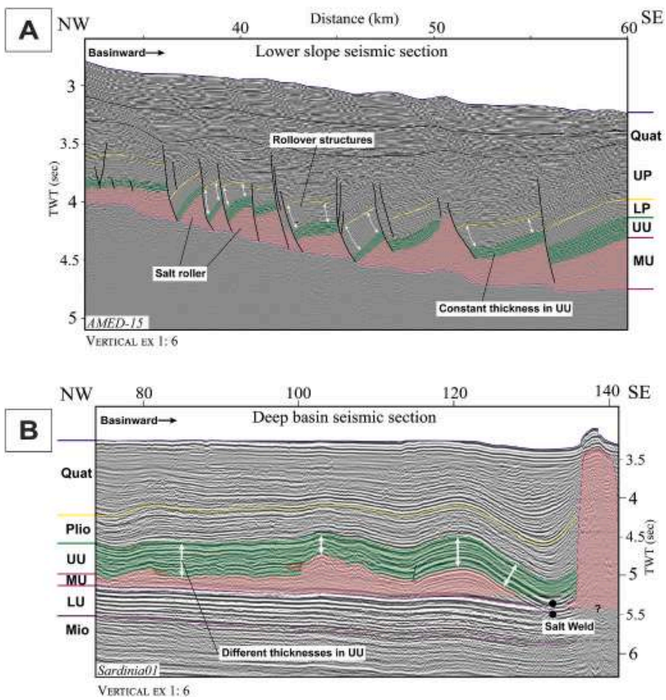


Fig. 2. (A) Zoom on high-resolution seismic profile of Gulf of Lion lower slope (location Fig. 1) showing salt rollers and rollover structures from the Early Pliocene deposits. (B) Zoom on low-resolution seismic profile (Fig. 3; location Fig. 2) showing early salt deformation syn-deposition of Upper Messinian Unit (green). The Lower Unit limit is from Lofi et al. (2011).

Lion: the frequency and size of diapirs change at the boundary between a transitional and an oceanic affinity crust (Fig. 3). Pautot et al., 1984 and Le Cann (1987) claim the reactivation of rifting-involved faults which could influence salt deformation and Maillard et al. (2003) an influence of differential compaction of subsalt sediments provided by basement steps filled by pre-Messinian sediments.

The specificity of the Messinian salt system and the coincidence observed in the Gulf of Lion (Fig. 3) have led us to extend the salt-structure/crustal-segmentation analysis to the whole Western Mediterranean Sea (Fig. 5).

3. Dataset and method

We compared salt morphologies and crustal domains in Western Mediterranean Sea margins, the Brazilian margin (Santos and Campos basins), the Angolan margin, the northern Gulf of Mexico margin, the north-west African margin and the Nova Scotia margin.

3.1. Salt morphology interpretation

In the Western Mediterranean Sea, we interpreted a large dataset consisting of seismic lines of various resolutions, collected through the French GDR Marges and Action Marges programs, with additional recent seismic data from OGS and Ifremer (Fig. 1). Reflection seismic lines have various resolutions and quality for good interpretation of deep and shallow reflectors. We interpreted salt structures in Liguro-Provençal and Algerian basins, leaving aside the Alboran Sea due to the absence of Messinian halite (e.g. Do Couto et al., 2014) and the Ligurian basin due to lack of data (Fig. 1). We defined a nomenclature for regional salt morphologies (Fig. 4) in order to classify them into five groups sharing the same geometrical features. The classification allowed to directly compare the salt morphologies to the crustal segmentation and nature and then to regionally discuss the salt structure genesis and evolution. The classification (Fig. 4) is mainly based on geometric criteria, such as: shape, base diapir width, geometrical relationship with the overlying layers and associated dominant features, such as faults, mini-basins (Jackson and Talbot, 1992) or welds (Jackson and Cramez, 1989). Although every salt structure is the result of process interaction, we tried to discriminate them only by their geometrical characteristics, without a detailed discussion on genesis and timing, to avoid model-dependent interpretation. The salt morphology groups are then map-plotted, showing vast variations between the proximal and distal domains and between the sub-basins composing the Western Mediterranean Sea.

In the Santos and Campos basins, we interpreted salt structures from published seismic profiles (Fig. 9) from Modica and Brush (2004); Mohriak et al. (2009, 2012); Torsvik et al. (2009); Lentini et al. (2010); Scotchman et al. (2010); Unternehr et al. (2010); Zalán et al. (2011); Davison et al., 2012; Kumar et al. (2013); Moulin et al. (2012); Peron-Pinvidic et al. (2013); Jackson et al. (2015); Strozyk et al. (2017); Kukla et al. (2018).

For the Angolan margin, we interpreted profiles (Fig. 10) from Marton et al. (2000); Tari et al. (2003); Hudec and Jackson (2004); Moulin et al. (2005); Unternehr et al. (2010); Fort et al. (2004); Cowie et al. (2016).

For the Gulf of Mexico, we compiled salt morphologies from several published seismic profiles (Fig. 11) (Wu et al., 1990; Radovich et al., 2007; Pilcher et al., 2011; Rodriguez, 2011; Fort and Brun, 2012; Hudec et al., 2013a; Ismael, 2014; Pindell et al., 2014; Rowan, 2014; Weimer et al., 2017; Curry et al., 2018; Liu et al., 2019) and from already published salt-distribution maps (Seni, 1992; Diegel et al., 1995; Peel et al., 1995)

Concerning the Morocco and Nova Scotia conjugated margins (Fig. 12), the salt structures interpretation originate from works by Hinz et al. (1982); Keen and Potter (1995); Sahabi et al. (2004); Shimeld (2004); Neumaier et al. (2016); Tari et al. (2000, 2003); Tari and Jabour (2013)

3.2. Crust segmentation

Crustal segmentation is constrained by wide-angle profiles from ECORS and SARDINIA Experiments (Pascal et al., 1993; Gailler et al., 2009; Moulin et al., 2015; Afilhado et al., 2015) in the Liguro-Provençal basin and by SPIRAL Project (Leprêtre et al., 2013; Medaouri et al., 2014; Mihoubi et al., 2014; Badji et al., 2015; Bouyahiaoui et al., 2015; Hamai et al., 2015; Arab et al., 2016; Aïdi et al., 2018) in the Algerian Basin. The lack of published wide-angle surveys in the South Balearic basin compels us to use the segmentation of this margin derived from gravity and magnetic data interpretations (Leroux et al., 2019).

For the Santos and Campos basins, we used the crustal interpretation from the SanBa Project (Evain et al., 2015) and for the Angolan margin, the Zaiango Project (Contrucci et al., 2004a, 2004b; Moulin et al., 2005; Aslanian et al., 2009). For the Gulf of Mexico, segmentation interpretation is from the refraction seismic project GUMBO (Eddy et al., 2014, 2018; Christeson et al., 2014; Van Avendonk et al., 2015) and interpretation from (Hudec et al., 2013a; Sawyer et al., 1991; Curry et al., 2018). For the Morocco-Nova Scotia conjugated margins, crustal segmentation is outlined from Biari et al. (2015); Contrucci et al. (2004a, 2004b); Funck et al. (2004); Wu et al. (2006).

4. Western Mediterranean salt morphologies - description and distribution

In this chapter we will describe the main present-day salt-morphology characteristics (Fig. 4) and their spatial distribution along the Western Mediterranean Sea (Fig. 5). Fig. 6 (A, B, C, D, E) and Fig. 7 (F, G, H, I) present nine seismic transects across the different sub-basins. The profiles provide a regional view of salt morphologies following the nomenclature described in Fig. 4 and respectively highlight: (1) the Liguro-Provençal basin (LPB): the Gulf of Lion margin and the western Sardinia margin (Fig.s 6A; 7F,G); (2) the east Algerian Basin (EAB) and

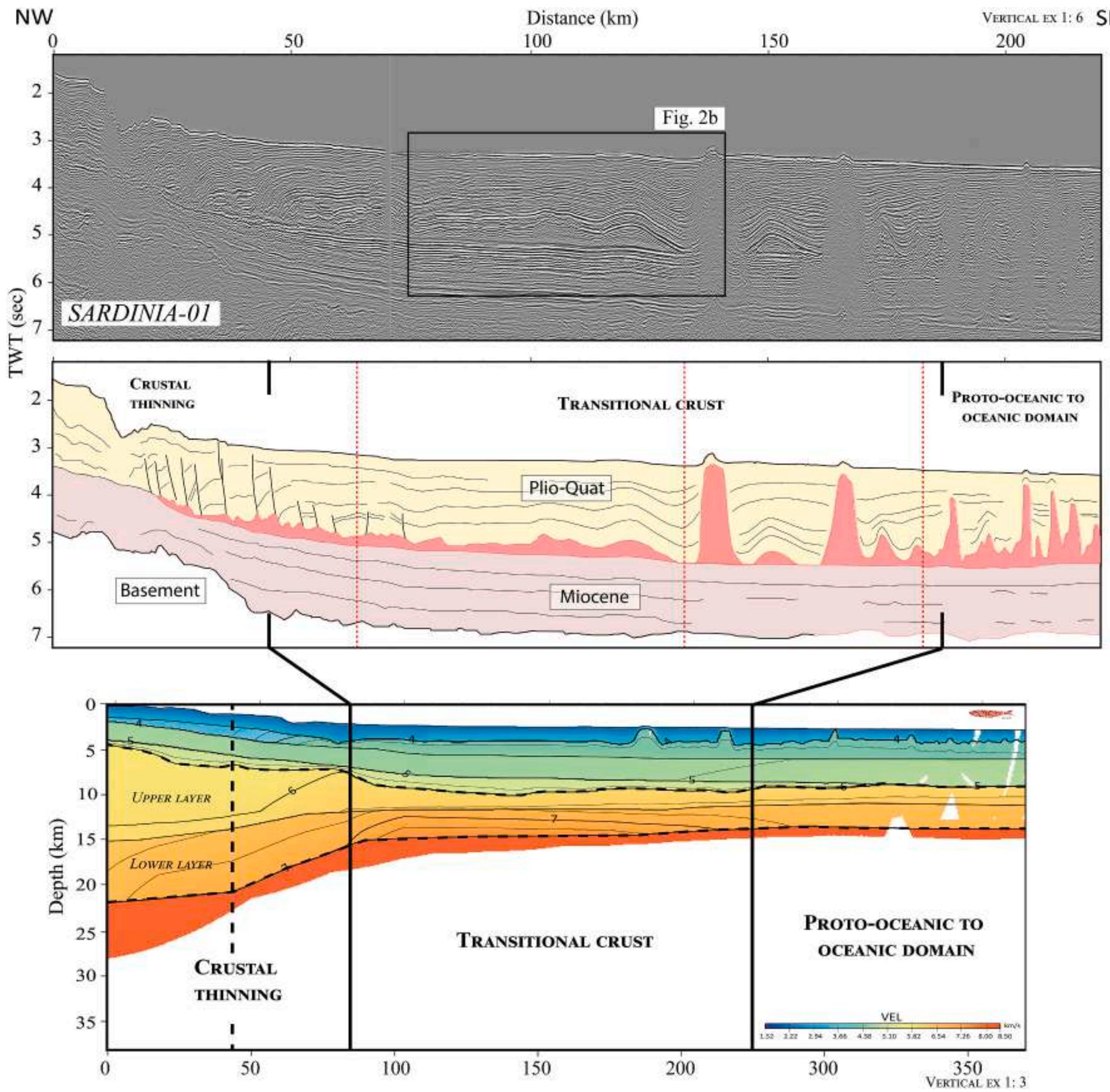


Fig. 3. From top to bottom: NW-SE Sardinia 01 time-migrated seismic profile, uninterpreted and interpreted (location in Fig. 1). At the bottom, Sardinia 01 wide-angle refraction profile showing crust segmentation along Gulf of Lion margin (modified from Moulin et al., 2015). Dashed black lines represent the lower and upper limit of the crust.

the southern part of the Liguro-Provençal Basin by crossing the North Balearic Fracture Zone (NBFZ, e.g. Olivet, 1996) (Fig.s 6B,C; 7H); (3) the western Algerian Basin (WAB) and the EAB by crossing the Hannibal Area (Fig. 6C); (4) the eastern and western part of the WAB (Figs. 6D,E; 7I). These long transects show the relationship between salt morphologies and crustal segmentation throughout the Western Mediterranean Sea and the regional salt structures variations, summarized hereafter:

- The Extensional domain is characterized by salt rollers and rollover anticlines and basinward-dipping normal faults involving the displacement of the Upper Unit and Plio-Quaternary deposits (e.g. Fig.s 6A; 7I). The faults can be active or buried (e.g. Gulf of Lion, Dos Reis, 2001) and are located at the mid-lower slope of the margins. The sliding of salt along its base detachment induces a sediment subsidence and thinning of salt, which is proportional to the density and thickness of the overburden and the initial salt layer thickness (Vendeville, 2005), and does not affect the pre-salt sequence (thin-skinned tectonics). The structures formed by salt movement are the results of an extensional process, which involves salt and overburden basinward movement. This domain is located at the mid-lower continental slope of the margins (Fig.s 6; 7) and is always present albeit with some differences in extension perpendicular to the margin, mainly as a result of the base of salt steepness and width of the margin (Fig. 5): in the Gulf of Lion it occupies an area that can extend up to 50 km basinward from the upslope limit of salt (Fig. 6A) while in the Algerian margin and in the east Alboran margin it is narrower by 10-20 km (Figs. 6B,D; 7I). In the south Balearic and in the western Sardinian margins it is between 10 and 30 km (Fig.s 6C,E; 7F,G,H). As mentioned above (Fig. 2a), the listric faults activated after the deposition of the Upper Unit and were mainly active in the Pliocene but they can reach the seafloor (Badhani et al., 2020).
- The Anticlinal salt domain (Fig. 4) is characterized by the absence of normal faults detached within the salt and it consists of anticlinal salt-cored and sparsely distributed normal faults at the top. The outer-arc extension faults are mainly located at the top of the Upper Unit affecting the Lower Pliocene sequence. The base of salt can be sub-horizontal (Gulf of Lion; Fig. 3) or even dipping landward, as in the north Algerian margin (Fig. 6B,D). The base of anticlines is large and the ratio between length and height is greater than five. The Anticlinal domain is located in the proximal deep basins (Fig. 5), characterized by a purely vertical subsidence (as shown in the Gulf of Lion by Rabineau et al., 2014; Leroux et al., 2015 and as also attested by sub-horizontal pre-salt deposits). It is not present in the western Sardinia, south Balearic and north-western Algerian margins, where the deep basin is

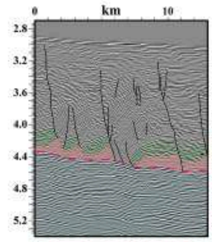
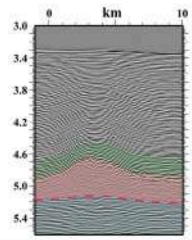
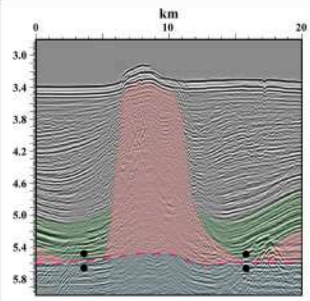
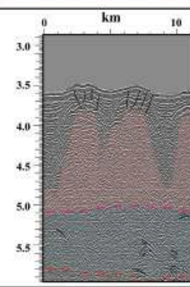
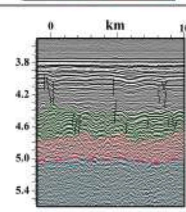
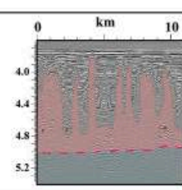
Name	Description	Seismic	Min Lenght	Min Height	Related structures
Extensional	Extensional domain located at lower slope. Characterized by thin-skinned tectonics. The Extensional domain is characterized by salt rollers, rollover anticlines. They generated from regional extension due to basinward salt flow. Basinward dipped base of salt. Listric faults, locally still active. Trasparent to chaotic seismic facies.		1 km	0.1 s twt	Basinward dipping listric faults involving displacement into Upper Unit and Plio-Quaternary units. No base salt and pre-salt displacement. The base of salt acts as detachment surface. Clear growth sequences in the Pliocene deposits.
Anticlinal	Wide base (up to 5 km), absence of persistent diapirism. Pillow large scale deformation that can affect the seafloor. Overburden (even the Upper Unit) concordant with salt top. Very high positive ratio of lenght to height (>5). Absence of listric landward-dipping faults. Trasparent seismic facies.		5 km	0.2 s twt	Locally, outer-arc extension faults over the roof of salt, mostly located above the Upper Unit. Base of salt sub-horizontal and not faulted.
Large isolated diapirs (GoL)	Wide base and piercing diapirism, still active. Ratio of lenght-to height between 0 and 1. Discordant overburden. They deform the seafloor, form evolved minibasin and weld in the diapirs flanks. Transparent seismic facies. Upper Unit «compressed» or eroded at the top.		3 km	1.0 s twt	Locally, outer-arc extension faults over the roof of salt. Base of salt sub-horizontal and not faulted. Salt lateral expulsion induced minibasins subsidence and locally salt welds.
Large diapirs (WAB)	Wide base and piercing diapirism, locally still active. The stocks and walls structures are closer than in the GoL. Ratio of lenght to height close to 0. Discordant overburden. They locally deform the seafloor and rare form weld between them.		2 km	0.8 s twt	Locally dissected by small contractional faults in the Upper Unit and extensional faults in the Plio-Quaternary deposits. Rare weld.
Connected regular	Close small diapirs which never deform the seafloor and almost never the Quaternary deposits. Sub-horizontal base salt. Ratio of lenght to height close to 1. Predominantly chaotic seismic facies.		0.5 km	0.3 s twt	Locally dissected by small contractional faults in the Upper Unit and extensional faults in the Plio-Quaternary deposits.
Connected irregular	Close, frequent and persistent diapirism. They always deform the Pliocene and Quaternary sequences and, often, the seafloor. The base is narrow. Ratio of lenght to height close to 0. Predominantly transparent facies.		0.5 km	0.8 s twt	Locally dissected by extensional faults in the Plio-Quaternary deposits.

Fig. 4. Salt morphologies nomenclature and description used in the Western Mediterranean Sea. Seismic zooms are all presented at the same scale to enable comparison. Vertical exaggeration 1:4.

dominated by diapir structures characterized by discordant overburden (Fig.s 6C,D,E; 7F,G,H). As shown in the Gulf of Lion (Fig. 2b), the anticlinal structures began to grow early, just after their deposition, during the deposition of the Upper Unit still belonging to the Messinian Salinity Crisis time. The evolution of structures in the Plio-Quaternary, not analysed in detail in this paper, seems to show an alternation of quiescent (mainly during the Pliocene) and more intense (during the Quaternary) deformation phases (e.g. Figs. 2B, 3).

- The Large Isolated Diapir (GoL) (Fig. 4) and the Large/Connected (WAB) domains exhibit piercing diapirism affecting the seafloor. In the

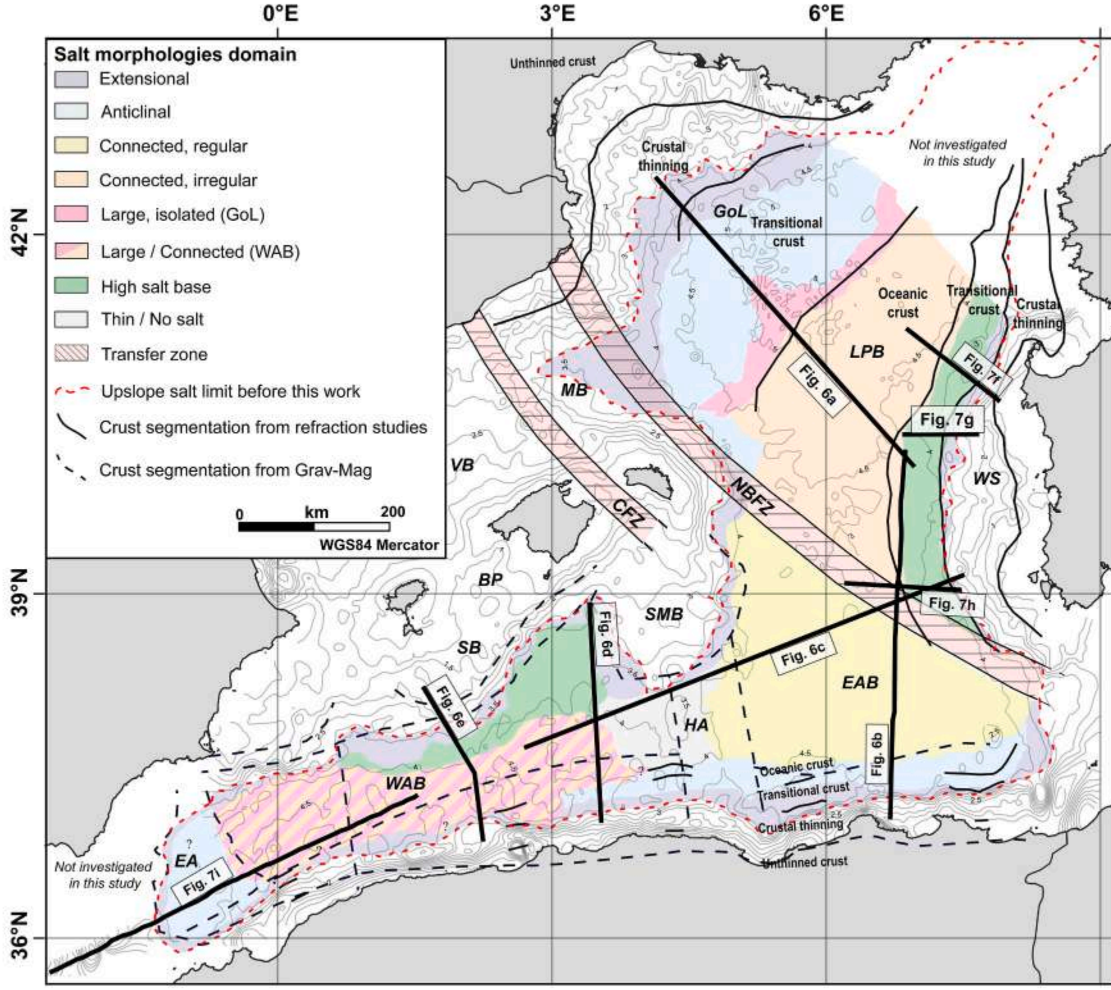


Fig. 5. Map showing the distribution of salt morphologies and crust segmentation in Western Mediterranean Sea. The contour lines represent the base of MUM unit (Gorini et al., 2015) in the deep basin and the BES (Basal erosional surface) and MES (Messinian erosional surface) (Lofi et al., 2011; Gorini et al., 2015) in the slope and shelf domains. In the deep basin, within the red dashed lines, the base of MUM unit represents the base of salt. Dashed red line represents salt upslope limit before this work, taken from Bache et al. (2009), Obone-Zue-Obame et al. (2011), Driussi et al. (2015). Contour every 500 m. The categories associated with the different colours are described in Fig. 4. Solid black lines correspond to the crustal segmentation from Moulin et al. (2015) (Gulf of Lion), Afilhado et al. (2015) (West Sardinia) and Leprêtre et al. (2013); Medaouri et al. (2014); Mihoubi et al. (2014); Badji et al. (2015); Bouyahiaoui et al. (2015); Aïdi et al. (2018) (north Algerian margin). Dashed lines represent segmentation interpretation from gravity and magnetic data (Leroux et al., 2019). Transfer zones are from Rehault et al. (1985) and Pellen et al. (2016).

Gulf of Lion (Fig. 5), diapir crests can rise to 250 m above the seafloor (Pautot et al., 1984) and the structures are isolated, forming wide mini-basins, welding together (Fig. 3). In the western Algerian deep basin, the structures are less spaced-apart and generally smaller in size (Figs. 5; 7I). In both basins, the overburden is discordant except for the Upper Quaternary sequence, which is concordant to the top of structures. The overburden deposits can form narrow and steep or, less frequently, gentle drape-fold geometries on diapir flanks, typical of hook and wedge halokinetic sequences described by Giles and Rowan et al. (2012) (see also Mianaekere and Adam, 2020). Salt stocks and walls are present: in the Gulf of Lion, the salt walls have a dominantly N-S direction while in the north Algerian margin they are parallel to the margin, as also described by Badji (2014) and Leprêtre (2012). In the Gulf of Lion they grew far from the upslope salt limit (at least 100 km basinward; fig.s 5; 6A) while in the west Algerian basin they appear closer to the margin (about 10 km, just basinward of the Extensional domain; fig. 5) and dominate the deep basin. The structures show an initial active growth history soon after the deposition followed by a passive down-building which characterized mostly all Plio-Quaternary diapirs.

- The Connected, Regular and the Connected, Irregular domains (Fig. 4) are interpreted for the deep basins (Fig. 5) and characterized by different-sized connected diapirs (Fig.s 6, 7). The Connected, Regular domain is characterized by closely-spaced diapirs that deform the Pliocene but very rarely the Quaternary sequences (Fig. 6B, C). The overburden reflectors are mainly concordant and the width to height ratio is close to one. This domain is located in the EAB, where a maximum salt thickness of 0.5 s twt and a regional sub-horizontal base characterize the entire basin (Figs 5; 6B,C). The Plio-Quaternary sedimentary thickness is more or less constant in all basins, except in the northeastern Algerian margin, with a mean thickness of 0.8 s twt. The Connected, Irregular domain is characterized by close and frequent diapirs (Figs. 6A; 7F). The overburden is mostly discordant and the structures are smaller and narrower than in the Large Diapir domain previously described: they have developed more in height than in width (Fig. 4) and can deform the seafloor.

In addition to the salt morphology domains described above, we interpreted two areas where the base of salt is around 500 m shallower than in the deep basin (Fig. 5). In the western Sardinian and south Balearic margins (Figs. 6B,C,D,E; 7F,G,H) the base of salt extends for 50 km (western Sardinian) to 20-100 km (south Balearic) from the

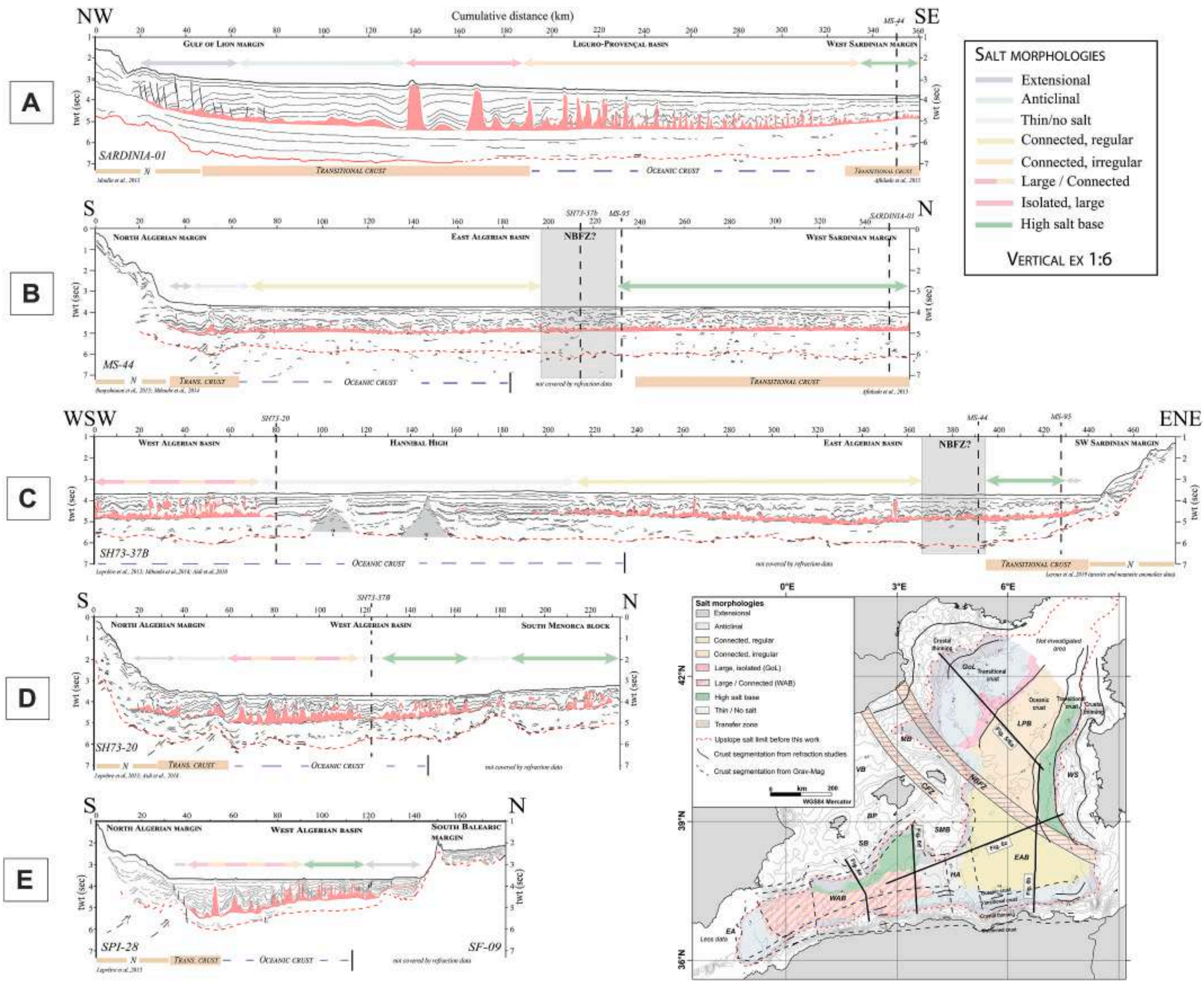


Fig. 6. Regional line drawings of seismic sections from the Gulf of Lion to the West Algerian margin (location in Fig. 5). The main salt morphologies domains in Western Mediterranean Sea are represented. The crustal segmentation is from literature (references are shown below the segments). Position of the Transfer Zone is from Pellen et al. (2016). Note the horizontally pre-salt and base salt reflectors and the salt morphology differences between east (B-C profiles) and west (C-D-E) Algerian sub-basins. Vertical exaggeration 1:6.

Extensional domain, located in the lower slope, and is low and basinward tilted. The diapir structures are close and connected. In the south Balearic margin (Fig. 6E) the sudden deepening of the salt base could be provoked by a southward basement tilting associated with the compressive reactivation of the Algerian margin (Leprêtre, 2012).

We also observed an area of thin or absent salt (hard to decipher with our seismic data resolution), concomitant with the Hannibal Area between the east and west Algerian basins (Fig.s 5; 6C). Here the salt is not deformed and, where present, has a maximum thickness of 0.2 s twt. The Hannibal Area is characterized by positive magnetic anomalies (Aïdi et al., 2018) and basement highs (Mauffret et al., 2004), which suggest the presence of magmatic structures (Fig. 6C).

5. Crustal segmentation and nature

The SARDINIA Experiment acquired, three wide-angle profiles in the Gulf of Lion (Moulin et al., 2015) and three in the Western Sardinian margin (Afilhado et al., 2015) (Fig. 1). The authors interpreted each margin in three domains, with possible subdomains, as also described by Bache et al., 2010 (Figs. 3; 5). These domains are similar between the conjugate margins, showing a symmetrical distribution (Gailler et al., 2009), except for the dimensions of the transitional domain, which is wider in the Gulf of Lion (Fig. 5). The first domain, which follows the onshore, unthinned continental crust domain, is the "crustal-thinning" domain, area characterized by the main thinning of the crust, mainly focused on the lower crust where, in the Gulf of Lion, its thickness decreases from 15 to 7 km (Fig. 3). Basinward, the transitional domain is characterized by a relatively high crustal velocity, varying between 6.0 and 6.4 km/s for the upper layer, and 6.6-7.5 km/s, 6.8-7.25 km/s for the lower layer, in the Gulf of Lion and West Sardinian, respectively. The lower layer is interpreted as exhumed lower continental crust (Moulin et al., 2015; Afilhado et al., 2015) or exhumed lower crust and upper mantle (Jolivet et al., 2015). The central domain is characterized by a decrease in velocity and velocity gradient in the lower crust (Moulin et al., 2015) and presents an "atypical" relatively thin (5 km) oceanic crust (e.g. Le Douaran et al., 1984; Gailler et al., 2009; Moulin et al., 2015). The oceanic crust is thinner than the Atlantic type but the velocity and gradients confirm the oceanic nature (Gailler et al., 2009) and its close relationship with the transitional domain, regarding velocities and Moho discontinuity depth (Moulin et al., 2015; Afilhado et al.,

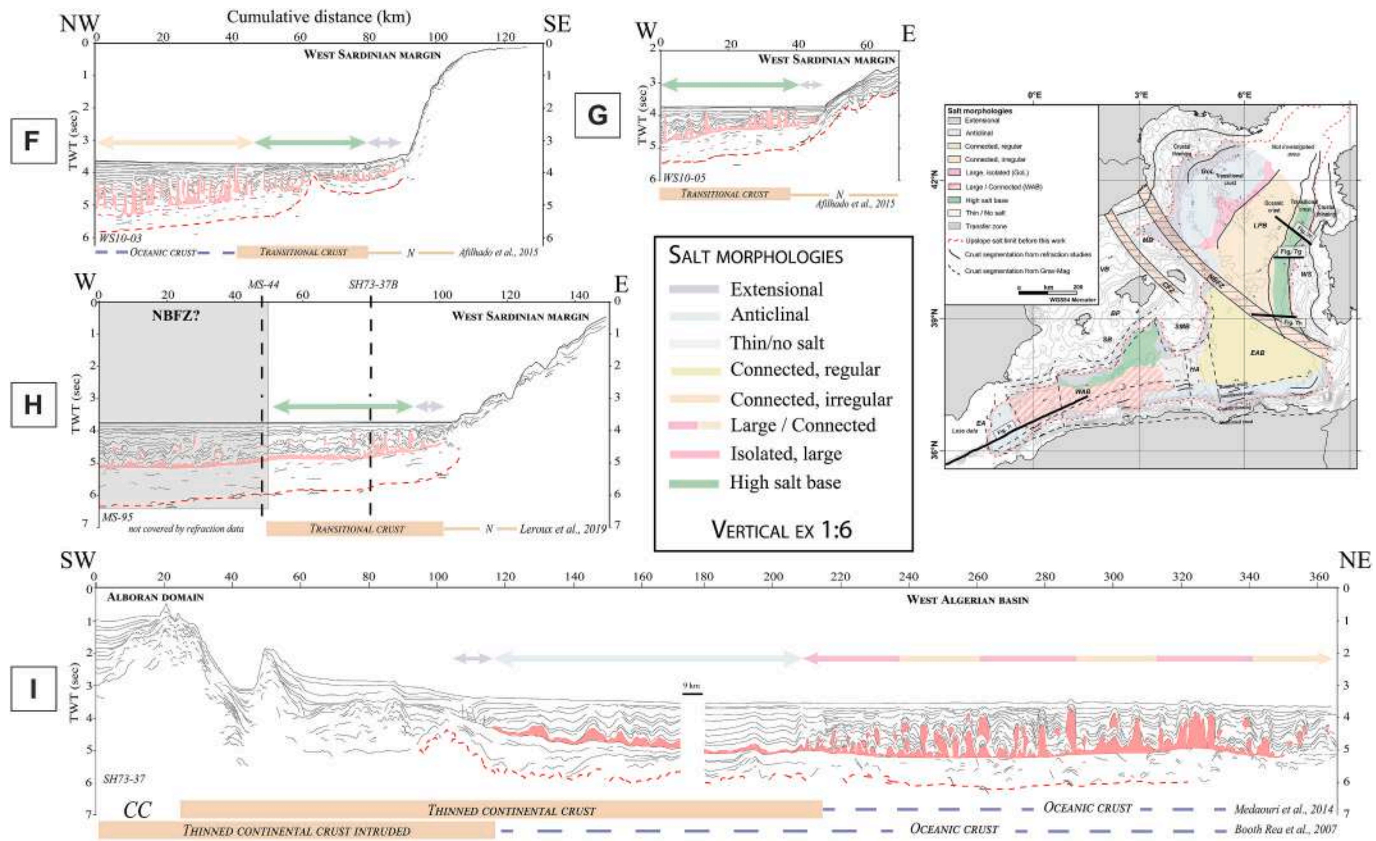


Fig. 7. Additional regional line drawings in Western Sardinian and West Algerian margins (location in Fig. 5), (same colour-code as previous Fig.s).Vertical exaggeration 1:6.

2015). Segmentation is confirmed by gravimetric (Smith and Sandwell, 1997) and aeromagnetic (Galdeano and Rossignol, 1977) data (Leroux et al., 2019).

Whilst in the EAB a well-organized set of N-S to NW-SE magnetic anomalies suggests an oceanic nature for this basin (e.g. Leroux et al., 2019), in the WAB the absence of clear aligned magnetic anomalies suggests a clear oceanic crust, leaving open the question as to the crustal nature and consequently the geodynamic models of the area. The results of the SPIRAL wide-angle survey show a narrow, thinning continental crust domain (from 20 to 60 km wide) (Fig. 5) along the entire Algerian margin with possible heterogeneous thinning between the upper and lower crust in some transects (Leprêtre et al., 2013; Arab et al., 2016; Aïdi et al., 2018). Likewise, the transitional domain is narrow (Fig. 5), often associated with graben structures at the surface and interpreted by some authors as the surface expression of the subduction-transform edge propagator (STEP) fault (Govers and Wortel, 2005) with several accretion axes (Badji et al., 2015; Aïdi et al., 2018). The SPIRAL refraction results show a central part of the Algerian basin characterized by a 5.5-km-thick crust with velocity differences between the sub-basins that lead the authors to interpret their nature as follows: (i) the EAB is composed of magmatic thin crust (Mihoubi et al., 2014; Bouyahiaoui et al., 2015); (ii) the Hannibal High could have undergone a magmatic reworking during the second phase of basin opening (Aïdi et al., 2018); (iii) in the WAB the presence of some mantle serpentinization is possible (Aïdi et al., 2018). New heat flow data suggests different formation ages (Poort et al., 2020), confirming the contrasting geodynamic sub-basin history.

6. Discussion

6.1. Geometrical correlation between salt morphologies and crustal segmentation

There is correlation between salt morphology and the structural segmentation and nature of each sub-domain of the Western Mediterranean area (Figs. 5; 6; 7). In the Liguro-Provençal basin, the Extensional domain is located on the edges of the margins, where the authors interpret a transitional and/or thinned crust (Moulin et al., 2015; Afilhado et al., 2015), along the entire north Algerian margin (Leprêtre et al., 2013; Mihoubi et al., 2014; Badji et al., 2015; Bouyahiaoui et al., 2015; Aïdi et al., 2018) and at the transition between the WAB and the Alboran basin (Medaouri et al., 2014). In the western Sardinian margin, the boundaries of the high salt base domain match well with the transitional crust interpreted by Afilhado et al. (2015). In the deep Liguro-Provençal basin the Connected, Irregular salt morphology corresponds to a proto-oceanic and/or oceanic crust following the interpretation of refraction data by Moulin et al. (2015) and Afilhado et al. (2015). A Connected, Regular domain is interpreted in the EAB, which appears to correspond to a thin oceanic crust, as shown by refraction data (Mihoubi et al., 2014; Bouyahiaoui et al., 2015) and clearly aligned magmatic anomalies (Leroux et al., 2019). The WAB, whose crustal structure is still a matter of debate, is generally characterized by further deformed salt structures, contrasting in the eastern and northwestern sectors: in the southwest of the South Menorca Block, the salt structures are connected and the salt base is shallower while the deep basin is characterized by the deepening of salt and larger morphologies. The transition between continental and oceanic domains in the Alboran-WAB limit corresponds to a change in salt morphologies, between an Anticlinal to a Large/Connected domain. The sharp and quick transition from a thinned continental crust to an oceanic crust along the north Algerian margin is associated with a rapid transition in salt morphologies, from an extensional domain to a diapir domain. This latter shows different size structures between the east and west Algerian deep basin.

6.2. Salt morphology segmentation hypotheses

We have mentioned some specific features of the Western Mediterranean which make it a distinctive area for a salt tectonics study in a passive margin context. The salt deposited during the Messinian Salinity Crisis (about 6 million years ago) in a closed system where all sub-basins considered in this paper were already formed, long after the rifting phases and oceanic spreading. The salt is therefore not involved in any rifting-extension movement, as some authors have claimed, for instance in the Gulf of Mexico (Hudec et al., 2013b). Consequently, the Mediterranean Sea salt was deposited throughout the deep, already-formed oceanic basins and lower slopes, onlapping the pre-salt sedimentary sequences. The lower slope (concomitant with the Extensional salt domain) is characterized by a basinward-tilting margin while the deep basin by a purely vertical subsidence, started just after the oceanic breakup (Rabineau et al., 2014; Leroux et al., 2015; Bache et al., 2010). The vertical subsidence suggests a constant initial salt thickness in all the deep basins, without the regional differences which can be provided by variations in accommodation space during the deposition. Initial salt thickness is hence predicted as constant throughout the deep basin, above a thick pre-salt sedimentary layer that covers all initial topographic variations, except for the margin edges, in the lower slope, where it was probably thinner. The tilting of the slopes effectively induced well-developed thin-skinned tectonics, as previously described by several authors (Gaullier, 1993; Dos Reis et al., 2005; Brun and Fort, 2011). Nevertheless, we have shown that the salt started to deform during the Messinian while the listric faults in the margin activated only in the Lower Pliocene. The infra-Messinian deformation was active throughout the deep basin, as also observed in the north Algerian (Bouyahiaoui et al., 2015) and western Sardinian margins (Del Ben et al., 2018) and was already observed in the Levant basin (Gvirtzman et al., 2013). If, as we anticipated, there was indeed a constant initial salt thickness and no salt translation at that time, an imbalance of salt flux (Pichel et al., 2020; Evans and Jackson, 2020), which could have created accommodation for growth sedimentation and so early differential loading, would be excluded. Another possible interpretation is that of an erosional phase infra-UU which could have created differential load in the early overburden, inducing early salt deformation. An infra-UU unconformity named IES (Intermediate Erosion Surface) is observed in the western Sardinian and south Balearic margins (Lofi, 2018; Geletti et al., 2014) and in the intermediate-depth basins, such as Valencia and east Corsica basins (Lofi et al., 2011). The IES shows erosional truncation and divides the UU into two sub-units. It is complex to apprehend whether the erosional surface is the cause or if it marks the end of the infra-Messinian deformation. In Fig. 2 the IES is not observed (probably due to the low resolution of the line) and the deeper sub-unit of the UU seems to onlap the salt. The link between the IES surface with respect to the infra-UU salt deformation is therefore still uncertain. Moreover, as shown in Lofi et al. (2011); Lofi (2018), the UU basin-scale lateral facies can vary. These variations could induce changes in the load above the salt, which could then locally induce an early movement of salt without lateral forces necessarily coming into play. Although early halokinetic movements could be observed in the presence of significant initial salt thickness, the striking coincidence between crustal segmentation and salt morphology remains unexplained.

Following Bache et al. (2012), the evaporites in the Mediterranean deep basin deposited during a relatively moderate and slow sea-level rise. The salt deposition was probably brief (<50 000 years, Bache et al., 2012) and the following dilution of waters led to the progressive deposition of the Upper Unit. The pure halite seismic facies and the rapid salt deposition in a relatively constant sea-level rise prompts us to exclude any erosive surfaces inside the salt that could have triggered differential spatial loading. Moreover, the seismic facies seems typical of pure halite and no regional lithological levels have been interpreted, as for instance in eastern Mediterranean salt deposits (Gorini et al., 2015; Gvirtzman et al., 2013; Evans and Jackson, 2021).

The main unresolved issue is the geometrical coincidence between salt morphologies and crustal segmentation (Figs. 3, 5, 6, 7). As mentioned, the salt is deposited above a thick (up to 2.5 km in Liguro-Provençal basin), regionally unfaulted, pre-salt sequence. The base of salt is also unfaulted and does not show regional, spatial depth variations (Figs. 6; 7). The only margin affected by thick-skinned tectonics is the north Algerian margin, which undergoes tectonic inversion caused by the NW-SE convergence between the African and European plates (e.g. Kherroubi et al., 2009). The present-day shortening causes the base of salt displacement by low angle south-dipping reverse faults (e.g. Domzig et al., 2006; Leprêtre, 2012; Déverchère et al., 2005; Leffondré et al., 2021) and the salt involving in the play of active ramps and flats (Fig. 6B,D,E). However, the north Algerian margin is a unique case within the Western Mediterranean Sea. An active tectonic influence is thus discarded as a possible cause of crustal-segmentation/salt-morphology coincidence.

Le Cann (1987) and Pautot et al. (1984) claimed that the reactivation of rifting-involved faults could influence salt-structure distribution while Maillard et al. (2003) discussed the influence of differential pre-salt sediment compaction. However, there is no observation to support that a main fault system could have affected the base of salt, since pre-Messinian sediments are thick and mostly unfaulted in the deep basin. The majority of inherited rifting faults are no longer active and there is no correlation between salt deformation and fault activation timing. We agree on the theory of basement-step relevance, even below a thick sedimentary sequence which may have smoothed any rugosity. However, unless probably for the North Balearic Transfer Zone (Fig. 5), there are no significant steps in the basement that could explain such a difference. Moreover, the physical experiments of Maillard et al. (2003) are unrealistically scaled, with a basement step three times the silicone thickness and a simulated base salt tilt of 3°, not observed in the deep basin. As highlighted in Fig. 3 (reflection and wide-angle profiles), at the transitional-oceanic crust boundary, the basement has small depth variations, pre-salt is mostly unfaulted and the base of salt is sub-horizontal. Moreover, the observations of Pautot et al. (1984) and Maillard et al. (2003) are mainly localized in the Gulf of Lion deep basin, while the crustal segmentation-salt morphology coincidence seems to be present throughout the Western Mediterranean sea.

It is widely known that sedimentary loading may be a dominant mechanism on passive margin salt tectonics (e.g. Vendeville, 2005; Rowan et al., 2012; Warsitzka et al., 2013; Gaullier et al., 2014). The progradation of a brittle sedimentary wedge over a buoyant salt layer induces pressure gradient differences caused by differential loading (e.g. Vendeville, 2005). In the Gulf of Lion, the Quaternary Rhône Fan represents a large turbidite system which consists of a 1500 m-thick accumulation of turbidites and mass-transport deposits (e.g. Leroux et al., 2017; Droz et al., 2020; Cattaneo et al., 2020; Badhani et al., 2020). The marked salt deformation in the deep Gulf of Lion basin occurred in the Quaternary and is often related to this sedimentary fan, which would have pushed and squeezed the salt towards the distal basin, forming salt stocks and walls (Large Diapirs domain, Fig. 5). Nevertheless, once again, this phenomenon cannot explain the coincidence between crustal segmentation and salt morphologies observed throughout the Western Mediterranean Sea. Moreover, Plio-Quaternary sedimentation is inconsistent in the deep sub-basins. It can reach 2 km in the Gulf of Lion basin but is, with lower thicknesses, almost identical in the EAB and in the WAB (less than 1 km). As described in Fig.s 5, 6 and 7, salt morphologies in the EAB and WAB differ considerably, questioning the role of sedimentary loading in both deep basins.

We propose that, despite being deposited above a thick sedimentary column, the salt layer could be affected by a crustal and mantle thermal anomaly. The main causes of salt tectonics, discussed here and well-known until now, seem to be inadequate in explaining the coincidence between crustal nature and salt morphology. The thermal segmentation seems to be the only hypothesis that could explain the observed correlation. Below, we provide elements in support of our hypothesis which remains to be proved and quantified, but which should not overlooked.

6.3. The potential role of thermicity on salt deformation

Since the hypothesis of thermal convection argued by Talbot (1978) heat influence on salt deformation has intrigued the salt tectonics scientific community. Following this author, geothermal gradients can add an extra component to the classic salt tectonic mechanisms. Salt rheology is mainly explained by creep equations, strongly affected by the properties, water content and temperature of salt grains (e.g. Li and Urai, 2016). Temperature plays an important role, causing a decrease in viscosity (Urai et al., 1986, 2008; Carter et al., 1993; Van Keken et al., 1993; Li and Urai, 2016; Marketos et al., 2016; Peach et al., 2001; Jackson and Hudec, 2017). For example, Carter et al. (1993) found a strong decrease in salt viscosity (up to four orders of magnitude) from a temperature of 0°C to 100°C. High temperatures are found adjacent to a rise of magma which may be the main cause of its movement (Schofield et al., 2014). In the southern North Sea, Underhill (2009) suggests heating induced by Paleogene dikes as a main trigger of salt movement. Recently, Magee et al. (2020) suggests a salt flow enhanced by the hot magma emplacement in the Santos basin. Moreover, salt morphologies seem to change near the sill-complex: where the sills are located, salt rollers are formed whilst far from the sill, the area is characterized by diapiric deformation (Magee et al., 2020). Post-rift volcanic activity is observed in several margins, as in the oceanic crust of the Gulf of Aden (Leroy et al., 2010) and in the Newfoundland and Labrador margins (Karner and Shillington, 2005). In the Gulf of Aden, Lucazeau et al. (2009) measured a very high heat flow concomitant with a volcanic structure, whose activity lasted well beyond the rifting phase. The magma transfer is closely related to fault-zones (Georgen and Lin, 2003) which could be inherited from the rifting period and can channelize heat distribution. Volcanic activity and magmatic intrusions can somehow influence salt morphologies, but they are local phenomena and do not fully explain the coincidence between crust and salt, observed at a regional level.

More regional thermal anomalies can be produced by a pronounced crustal heat segmentation. An extremely thinned crust with exhumed mantle or lower crust can, with the help of fluids, affect the thermal regime in a large transition zone and lead to regional variations in temperature at the base of the salt. The passive margin genesis is a complex process, where the lower continental crust and the upper mantle play a crucial role. Several indications provide insights into crustal and mantle thermal segmentation and its role on subsidence, such as: the discovery of serpentinized mantle in a few transitional domains (Boillot et al., 1980), the role of lower continental crust exhumation (Moulin et al., 2005; Aslanian et al., 2009; Afilhado et al., 2015; Moulin et al., 2015; Evain et al., 2015; Loureiro et al., 2018), anomalous heat flow in the transitional domain (Dupré, 2003; Lucazeau et al., 2008; Goutorbe et al., 2008a; Goutorbe et al., 2011), the role of mafic intrusion in the lower continental crust (Thybo and Nielsen, 2009; Thybo and Artemieva, 2013; Tozer et al., 2017; Moulin et al., 2020), the fact that the passive margins remain in a high position, close to sea level, until the breakup and even much later (Moulin et al., 2005; Aslanian et al., 2009; Labails et al., 2009; Péron-Pinvidic and Manatschal, 2009; Bache et al., 2010). The replacement of continental mantle by hot asthenosphere produces an important thermal anomaly that affects the subsidence of the transitional domain (Huismans and Beaumont, 2011, 2014). These thermal anomalies can be persistent in time due to edge-driven convection in the mantle and result episodically in heat rising to the surface through magmatic intrusion (King and Anderson, 1998; Lucazeau et al., 2008). Analysis of heat flow in the transitional crust domains estimates that these processes can lead to an increased mantle heat flow input of 20-30 mW/m^2 (Goutorbe et al., 2008b) and a doubling of the surface heat flow (Lucazeau et al., 2010). This equally means higher temperatures at the top of basement crust that will be transferred to the salt deposits. Moreover, regional hydrothermal circulations are known to occur in margins and can redistribute heat in specific margin segments (Lucazeau et al., 2010; Poort et al., 2020).

Although the direct link between salt morphology segmentation and the thermal regime remains speculative, we argue that the hypothesis of a relationship between temperature and salt deformation at a regional level should not be discounted. As the temperature increases, viscosity decreases and the strain rate increases. We would thus expect, with the same force and salt features (water content, grain size, purity...), a faster and more "intense" deformation at higher temperatures. Only more in-depth work on the thermal regime in passive margins can help in quantifying the temperature variations needed to affect salt flow.

7. Other salt passive margins

In the previous section, we described the coincidence between crustal segmentation and salt morphologies in the Western Mediterranean Sea. Although we have listed some of the hypotheses to explain this coincidence, discussion is still open and a clear answer still indefinite. In the next section, we will explore other, well-known, passive margins in the world (Fig. 8) to understand if this correlation is observed in other salt-bearing margin contexts. We will not detail the salt tectonics of every margin as this is not the object of this paper. Nevertheless, we will try to summarize the key information and analogies with the Western Mediterranean Sea, in order to discuss the salt morphology-crustal segmentation relationship. We compared regional salt morphologies and crustal segmentation in the South-Atlantic margins (Angolan and Santos basins), Gulf of Mexico, Morocco and Nova Scotia margins.

7.1. Salt morphologies

The definition of the salt morphology domain is not simple as each passive margin differs in main salt tectonic mechanisms and resulting structures. We have grouped salt morphologies into three main domains, for regional comparison with crustal domains constrained by refraction seismic data. The choice of only three domains falls on the impossibility of having the same detail of analysis as we have in Western Mediterranean. We have referred the salt structures interpretation to the wide salt

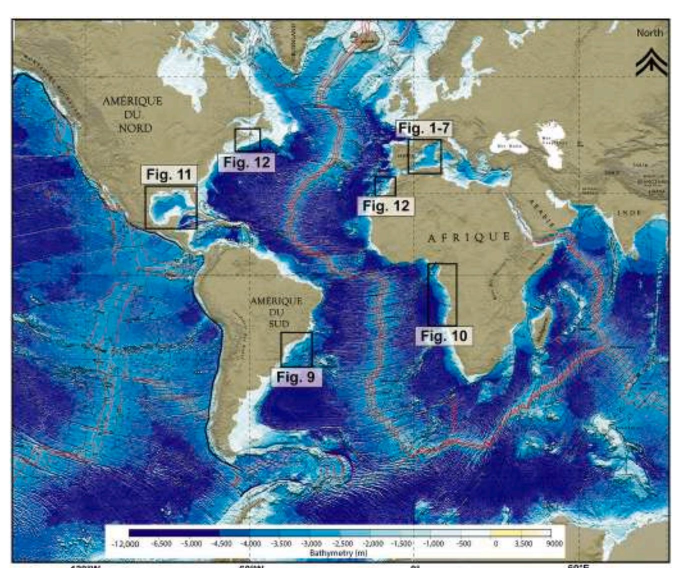


Fig. 8. Regional bathymetric map showing location of the world passive margins study areas.

tectonics literature present in the different passive margins, using published profiles (References in chapter 3.1) and salt isopach maps (e.g. Kukla et al., 2018; Mohriak et al., 2008).

The three domains are so-defined based on main geometrical characteristics and associated structures, as already the case for the Western Mediterranean Sea, for a global, homogenous perspective, and are named: –Extensional domain, –Diapir domain and -Massive-Canopy domain. The Extensional domain is so-called due to the typical extensional thin-skinned structures such as salt rollers, turtlebacks and base salt-rooted normal faults. The Diapir domain includes salt stocks and walls characterized by discordant, overburdened, autochthonous, connected or disconnected structures. Moreover, the Diapir domain of the Gulf of Mexico can exhibit coalescence sheets and allochthonous salt as well as basinward listric faults (Diegel et al., 1995; Fort and Brun, 2012). The Massive-Canopy domain is located in the downdip part of the salt basins and is characterized by thickening of salt deposits, thrust, folds and compressional diapirs. This domain can be characterized by massive thickened salt and/or canopy structures. The term canopy describes salt that is emplaced at stratigraphic levels above the autochthonous evaporites and consists of sub-horizontal or moderately dipping structures (Hudec and Jackson, 2006). The salt moved vertically from a single or multiple autochthonous feeder forming a salt sheet, which, after coalescence of numerous structures, could form a canopy. The spatial distribution of these three domains shares features with kinematically

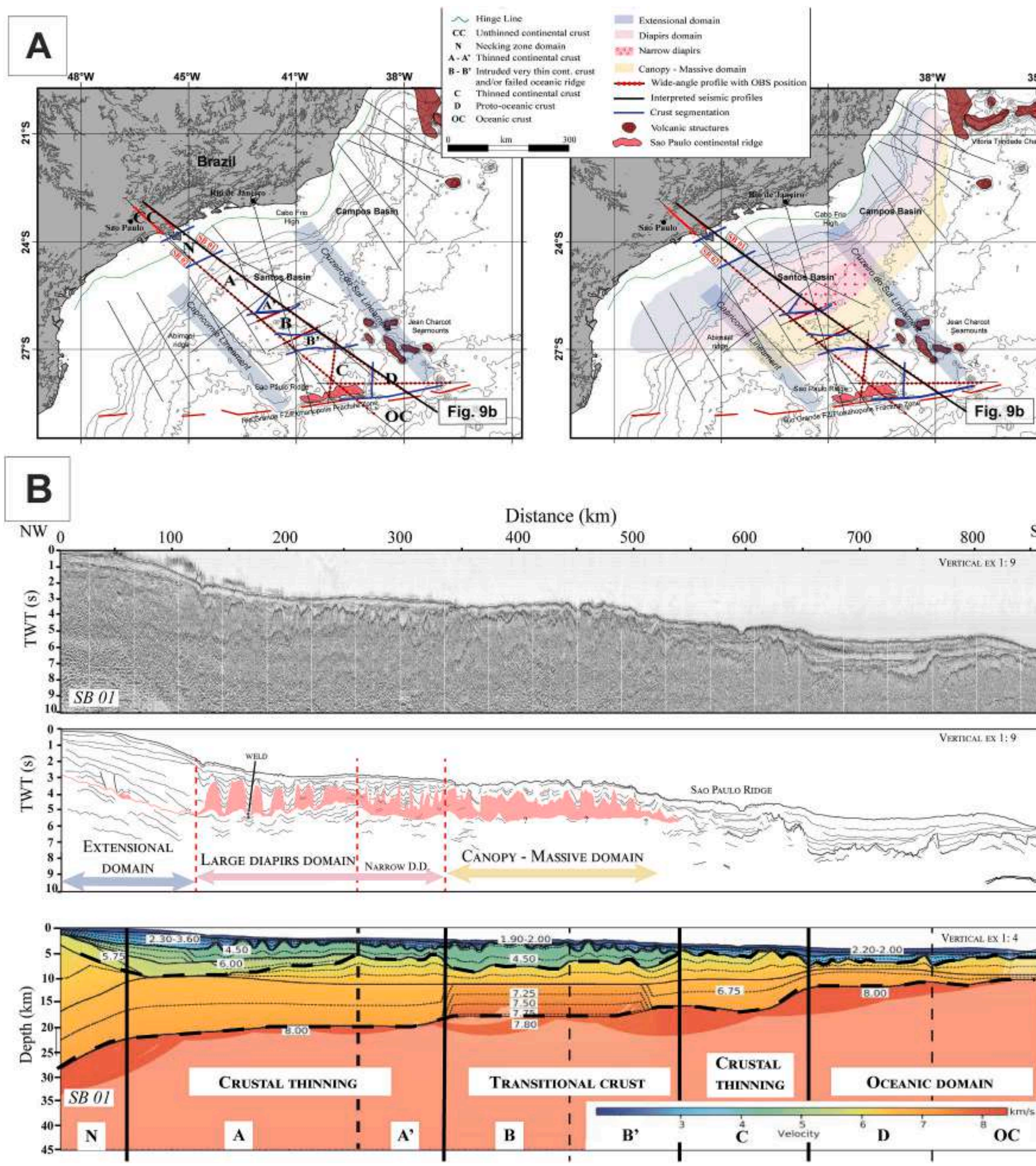


Fig. 9. (A) Map showing the salt morphologies and crust segmentation in the Santos and Campos basins. On the left it is shown only the crustal segmentation while on the right also the salt morphologies domains. Blue area represents the Extensional salt domain distribution; pink area the Large and Narrow Diapirs domains; yellow area the Canopy-Massive salt domain. Wide-angle profile location and crust segmentation are from Evain et al. (2015). Volcanic structures are from Mohriak (2001). The hinge line and the Capricornio and Cruzeiro do Sul Lineaments are from Moulin et al. (2012). Black lines represent seismic profile interpreted (references in the text). (B) From top to bottom, Sanba01 time-migrated reflection seismic line uninterpreted and interpreted (location in Fig. 9a). The interpreted salt morphologies are represented, showing their evolution from the lower slope to the deep basin. Sanba01 wide-angle profile, coincident with the reflection seismic line showing crust segmentation along SSPS (from Evain et al., 2015). Dashed black lines represent the lower and upper limit of the crust.

zones already described by authors (e.g. Brun and Fort, 2011; Hudec and Jackson, 2004; Jackson et al., 1994; Peel, 2014; Vendeville, 2005; Rowan et al., 2012), characterized by updip extension, mid-slope translation and a downdip contraction domain. We have not used the terminology already proposed in literature because we consider it interpretative with regard to the processes of salt tectonics involved. The Extensional domain in passive margins presents similarities to the Extensional salt domain described in the Western Mediterranean Sea. The Diapir domain has main similarities to the Large Diapir domain in the Algerian and Gulf of Lion deep basin (Figs. 6A and 10). The Canopy-Massive domain is not identified in Western Mediterranean salt basins, where the salt is mainly autochthonous.

7.2. Passive margins crustal segmentation

The crustal segmentation and nature of each margin is described in

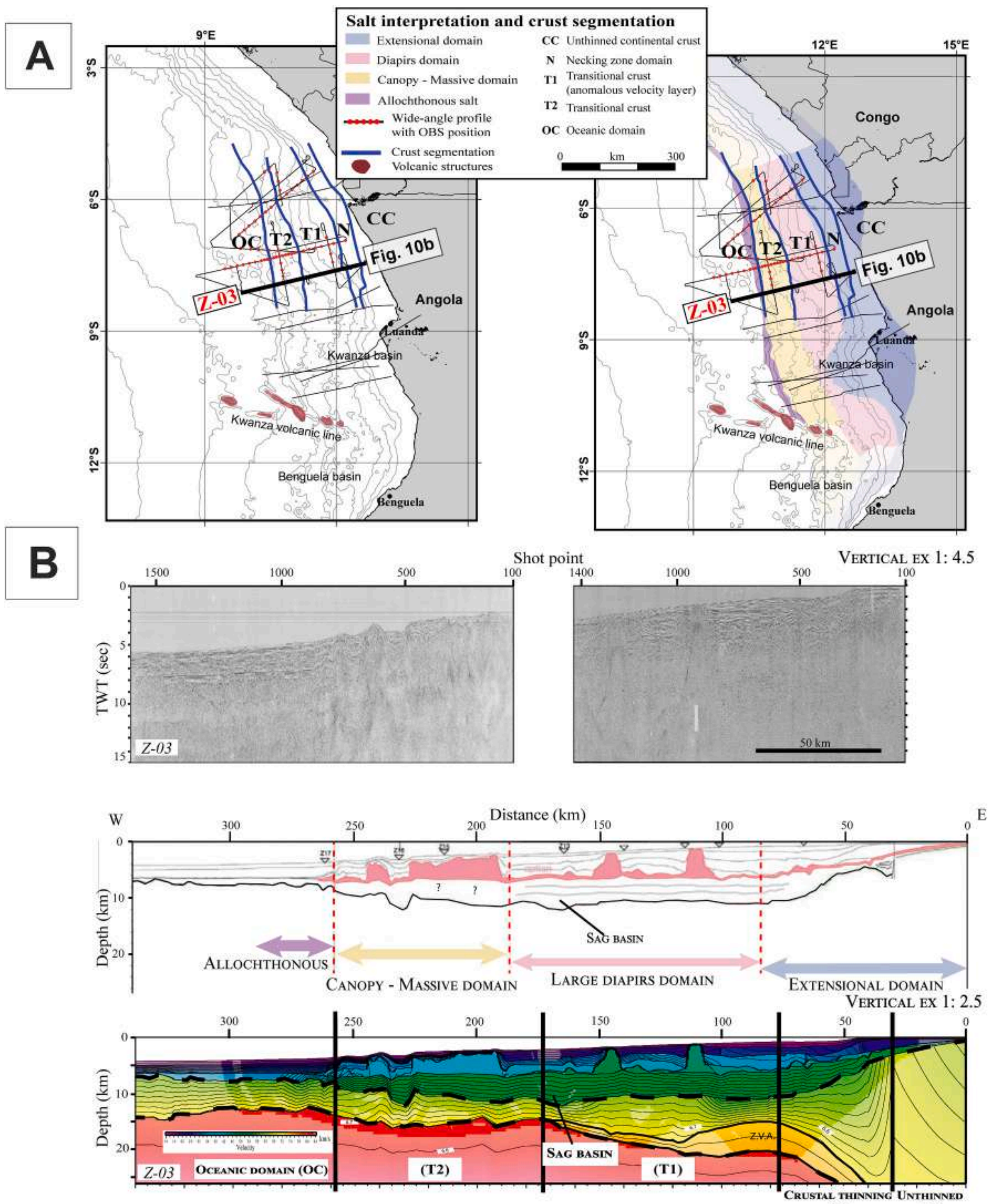


Fig. 10. (A) Map showing the salt morphologies and crust segmentation in Angolan margin. On the left it is shown only the crustal segmentation while on the right we have superposed the salt morphologies. Blue area represents the Extensional salt domain distribution; pink area the Large Diapir domain; yellow area the Canopy-Massive salt domain. Wide-angle profile location and crust segmentation are from Contrucci et al. (2004a) and Moulin et al. (2005). Black lines represent seismic profile interpreted in this study (references in the text). (B) From top to bottom, time migrated reflection profile and line-drawing interpretation (modified after Moulin et al., 2005) showing salt morphologies domains. Z-03 wide-angle coincident profile showing crust segmentation by Contrucci et al. (2004a). Location in Fig. 10a. Dashed black lines represent the lower and upper limit of the crust.

this paragraph, listing the interpretation proposed in literature. As in the Western Mediterranean sea, the segmentation is constrained by wide-angle seismic data with complementary gravity and magnetic data.

For the SSPS (Santos Sao Paulo plateau System), we used six multi-channel (MCS) and coincident wide-angle seismic profiles acquired during the SanBa Experiment on the Brazilian margin: profiles SB01 and SB02 run in a NW-SE direction, separated from each other by less than a hundred kilometers (Fig. 9a); profiles SB03, SB04, SB06 and SB07 cross these two main lines. The velocity models provided the authors (Evain et al., 2015) with new segmentation consisting of seven distinct domains (Figs. 9), also coherent with the observations of gravity and magnetic data:

- Domain CC: unthinned continental crust domain with a 35-40 km thick crust and velocities between 5.6 and 7.0 km/s.
- Domain N: the necking domain, characterized by thinning, is less than 100 km wide. The Moho rises and the basement deepens.
- Domain A: thin crust with velocities between 6.0 and 7.0 km/s. Towards the deep basin (SE), the Moho and the top of the basement rise slowly. This domain corresponds to a low gravity anomaly and a high magnetic anomaly and is defined as exhumed lower continental crust (Evain et al., 2015).
- Domain B: very thin crust that shows the most heterogeneous crustal structure. The basement deepens by 1-2 km and the area is characterized by a large and mostly negative magnetic anomaly and a relatively high gravity anomaly. Large lateral variations in crustal velocities are observed between the two profiles. This domain is interpreted either as very thin exhumed lower continental crust intruded by magmatism or as atypical oceanic crust, overlying altered mantle (Evain et al., 2015). Whatever the nature of domain B in the central part of the SSPS, it is characterized by a Moho rise, an extremely thin crust (7 to 11 km thick from Evain et al., 2015) and a lower layer characterized by high velocity (7.0-7.8 km/s) (Fig. 9b).
- Domain C: 11 to 17 km thick crust with a pattern similar to Domain A except for the lower upper crust velocity (5.2 km/s).
- Domain D: 5 km thick atypical crust with a triangular shape characterized by a step in bathymetry, low gravity and magnetic anomalies. Klingelhoefer et al. (2014) describe this domain as characterized by anomaly velocities as proto-oceanic crust.
- Domain OC: Oceanic crust

For the Angolan margin, we took into account the crustal nature interpreted after the ZaïAngo wide-angle project, led by Ifremer and TotalFinaElf. Seven MCS and refraction profiles were acquired between the Lower Congo and the Angolan basins (Fig. 10). Contrucci et al. (2004a) and Moulin et al. (2005) interpreted the Angolan margin formed by four domains (Fig. 10), also coherent with gravity and magnetic data:

- CC: corresponds to the unthinned continental crust, 30-35 km thick (based on gravity data)
- N: refers to the 50 km-wide necking zone, with an abrupt thinning of crust of about 20 km.
- T1: refers to the landward region of transitional domain characterized by a thin crust of about 16-8 km thick, and an anomalous velocity zone below (7.2 to 7.5 km/s). This layer is interpreted partly in the necking zone and it reaches a maximum thickness when the basin displays the maximum depth.
- T2: refers to the basinward region of transitional domain, characterized by a slightly thinning crust and the absence of the high velocity lower layer seen in T1. The transitional domain is bounded to the west by a basement high. Crust thickness does not exceed 5 km.
- OC: the oceanic crust is 6-7 km thick.

The velocity model in the upper crustal layer of segment T2 does not seem to be coherent with an oceanic nature and, at the same time, shows velocity and thickness that appear to be different to those of a "typical" continental crust (Contrucci et al., 2004a). The anomalous velocity layer in domain T1 can be interpreted as lower continental crust because of its velocities (Holbrook et al., 1992) or as serpentinized mantle (Contrucci et al., 2004a). Based on kinematic studies, wide-angle and multichannel seismic analysis, Aslanian et al. (2009) propose a three-phase model of evolution where domain T2 is allochthonous and could represent exhumation of the lower continental crust from the autochthonous T1 domain.

For the Gulf of Mexico, the crustal segmentation interpreted as part of the GUMBO Marine Seismic Experiment consists of four wide-angle profiles in the northern GOM margin (Fig. 11). The continental crust is between 36 km (Offshore Florida, Eddy et al., 2018) and 40 km (Huerta and Harry, 2012) thick and thins along about 200 km (Gumbo3, Eddy et al., 2014). In the transitional domain, the crust stretched to a thickness of less than 10 km (GUMBO1 offshore Texas, Van Avendonk et al., 2015; Fig. 7b), and 6-7 km offshore Florida (Christeson et al., 2014). In the northwestern GOM, concomitant to GUMBO3 and GUMBO4 profiles, the authors interpreted high-velocity lower crust as syn-rift magmatic intrusion into the lower crust (Eddy et al., 2014) while offshore Texas, the low velocity is not consistent with magmatic underplating (Van Avendonk et al., 2015). Here, a 45 km-wide zone of low-velocity and thin crust might be associated with exhumed mantle, locally serpentinized. The oceanic crust limit (OCT) is still debated in literature (Fig. 11). The oceanic crust has a thickness ranging from 6 km (offshore Florida, GUMBO4) to 8 km. Many interpretations of the nature of the transitional crust domain in the north GOM are proposed: thinned continental crust (Roberts et al., 2005); oceanic and proto-oceanic crust (Imbert and Philippe, 2005; Mickus et al., 2009); serpentinized mantle or thin oceanic crust (Kneller and Johnson, 2011); hyperextended continental crust with exhumed mantle in central and north-western sectors and proto-oceanic crust in the east (Rowan et al., 2012). Whatever the interpretation, the velocity models show a wide transitional domain characterized by a Moho rise (Fig. 11) (up to 16 km depth, GUMBO3) and crustal thinning (up to 7 km, GUMBO4), associated with high velocity in the lower layer (Fig. 11b).

In Morocco-Nova Scotia conjugated margins, we considered crustal segmentation using MIRROR (Biari et al., 2015), SISMAR (Contrucci et al., 2004b) and SMART (Funck et al., 2004; Wu et al., 2006) reflection-refraction experiments for, respectively, the Morocco (the former two) and Nova-Scotia margins (Fig. 12). The Moroccan margin segmentation is divided into three crustal domains (Fig. 12, from Biari et al., 2015): unthinned continental crust of 36 km thick, a thinning continental crust domain and an oceanic domain. The thinning domain is less than 90 km wide and, at the limit with the oceanic domain, the crust is approximately 13 km thick. The oceanic domain is characterized by an area with high lower crust velocities (atypical oceanic crust from Biari et al., 2015) and an oceanic crust thickness of 8 km in the most distal part. In the Nova Scotia margin (Fig. 12), Funck et al. (2004) (SMART1) and Wu et al. (2006) (SMART2) interpreted a 36 km-thick continental crust, which thins seawards to 5-6 km, mostly over the slope region. To the north (SMART1 and SMART2), the authors propose a wide area of partially serpentinized upper mantle rocks, characterized by high lower-crustal velocities (up to 7.6 km/s). Further south (SMART3) Louden et al. (2013) interpreted a thicker oceanic crust (7 km) and an area of magmatic underplated bodies. The comparison between the two conjugated profiles (SMART1 and MIRROR1), following the cinematic reconstitution of Sahabi et al. (2004), shows structural and crustal similarities in the area of the necking zone and a thinning of continental crust. However, the presence of a transitional domain in the Canadian margin characterized by an exhumed serpentinized mantle and a West African domain formed by intruded oceanic crust led the authors to favour the hypothesis of symmetrical rifting followed by asymmetrical oceanic accretion (Klingelhoefer et al., 2016; Biari et al., 2017), although there are other hypotheses, including an age difference between the two oceanic crusts imaged by refraction profiles or a greater

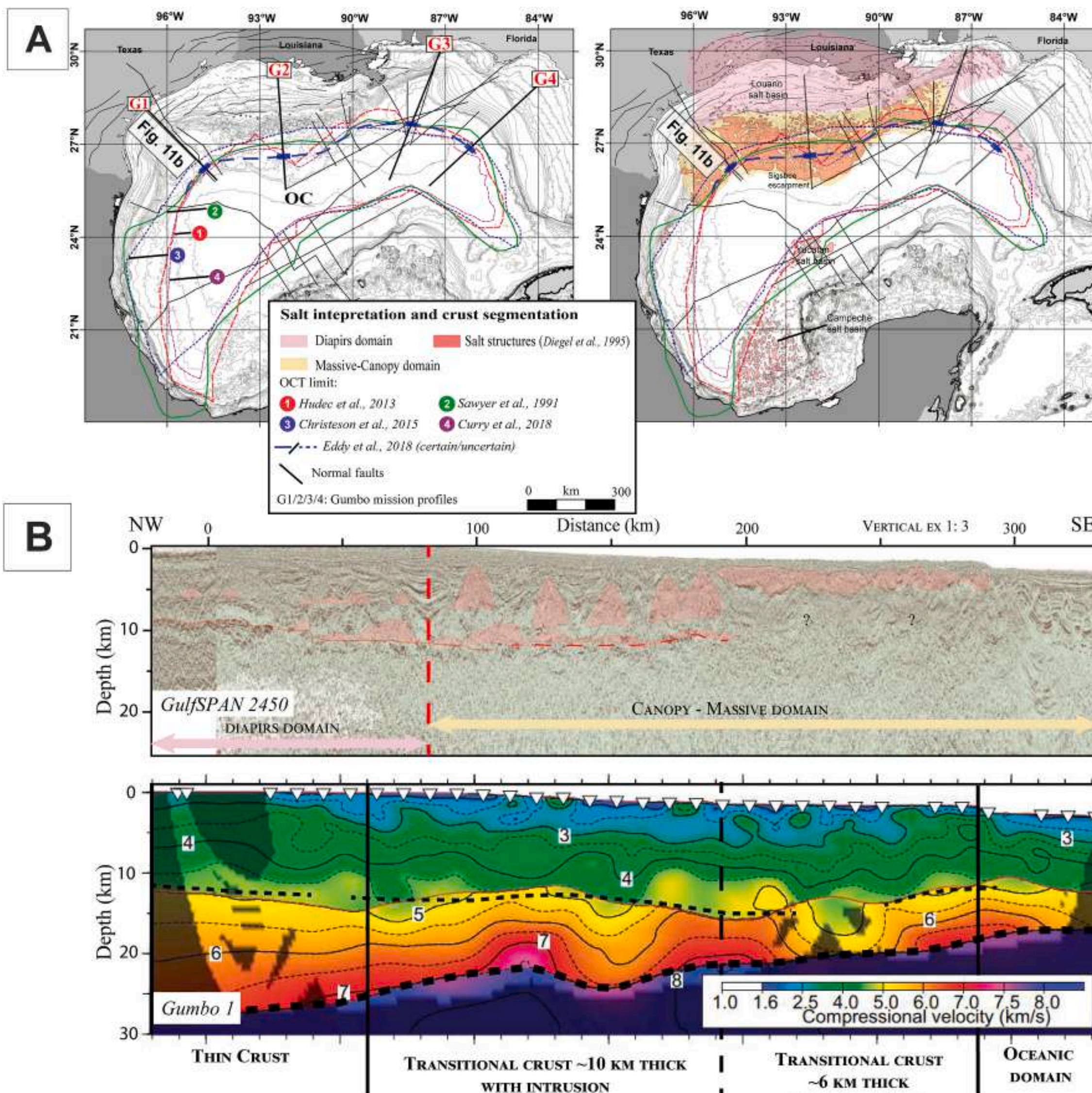


Fig. 11. (A) Map showing crustal segmentation and salt morphologies in Gulf of Mexico. On the left it is shown only the crustal segmentation while on the right the superposed salt morphologies. Outlined in red the salt structures from Diegel et al. (1995). Salt morphologies boundary are redrawn from Seni (1992). The oceanic domain boundaries from Hudec et al., (2013a); Sawyer et al. (1991), Christeson et al. (2014) and Curry et al. (2018) are represented. Black lines represent Gumbo wide-angle survey profiles (references in the text). Fault trends are from Diegel et al. (1995) and Stephens (2010). Black lines represent seismic profile, interpreted in this study (references in the text). (B) PSDM ION GulfSPAN 2450 profile from Van Avendonk et al. (2015) and (Dickinson, 2017) approximately in the location of GUMBO 1 profile (location in Fig. 11a). The salt morphologies are from this study. Below, the GUMBO1 wide-angle profile. Crustal segmentation in black is from this study and discussion in Van Avendonk et al. (2015). Dashed black lines represent the lower and upper limit of the crust.

thickness of the oceanic crust on the African side due to the influence of the Canary hot spot (Biari et al., 2015).

8. Geometrical correlation between salt morphologies and crustal segmentation in other passive margins and potential explanations

The spatial salt morphology distribution variation (Figs. 9; 10; 11; 12) suggests a relationship with the crustal segmentation of each margin.

In the Santos margin, the salt base is evidently interpretable except in the Massive-Canopy domain, where seismic imaging is hampered by absorption and scattering of salt deposits. In the Large Diapir domain, the salt base shows a landward vergence (Fig. 9b; Davison, 2007; Guerra and Underhill, 2012; Strozyk et al., 2017). Moreover, it is largely unfaulted in the proximal to distal domains and underlain by similarly unfaulted sag sequence (Moulin et al., 2005; Karner and Gambôa, 2007; Unternehr et al., 2010; Rowan, 2014), composed of syn-rift sediments (Kumar et al., 2013) of about 2 km thick (Evain et al., 2015). The transition between the continental domain (Domain A and A') and Domain B coincides with a change in salt morphology, from a Diapir Salt Domain to a Canopy-Massive Domain (Fig. 9). In Domain B the wide-angle profile shows an irregular top of crust (Fig. 9; dashed black line) but does not seem to have a structural influence on the salt. The SSSP represents a buffer zone of the South Atlantic Ocean (Moulin et al., 2012) with its two conjugate margins and a failed ridge in its centre (Evain et al., 2015). Therefore, in the southern part of the basin, the salt onlaps the Sao Paulo Ridge (Fig. 9), interpreted as of continental nature (Evain et al., 2015).

In the Angolan margin (Fig. 10), the slope exhibits an Extensional domain, described by various authors (e.g. Brun and Fort, 2011; Marton et al., 2000; Duval et al., 1992), basinward followed by the Diapir

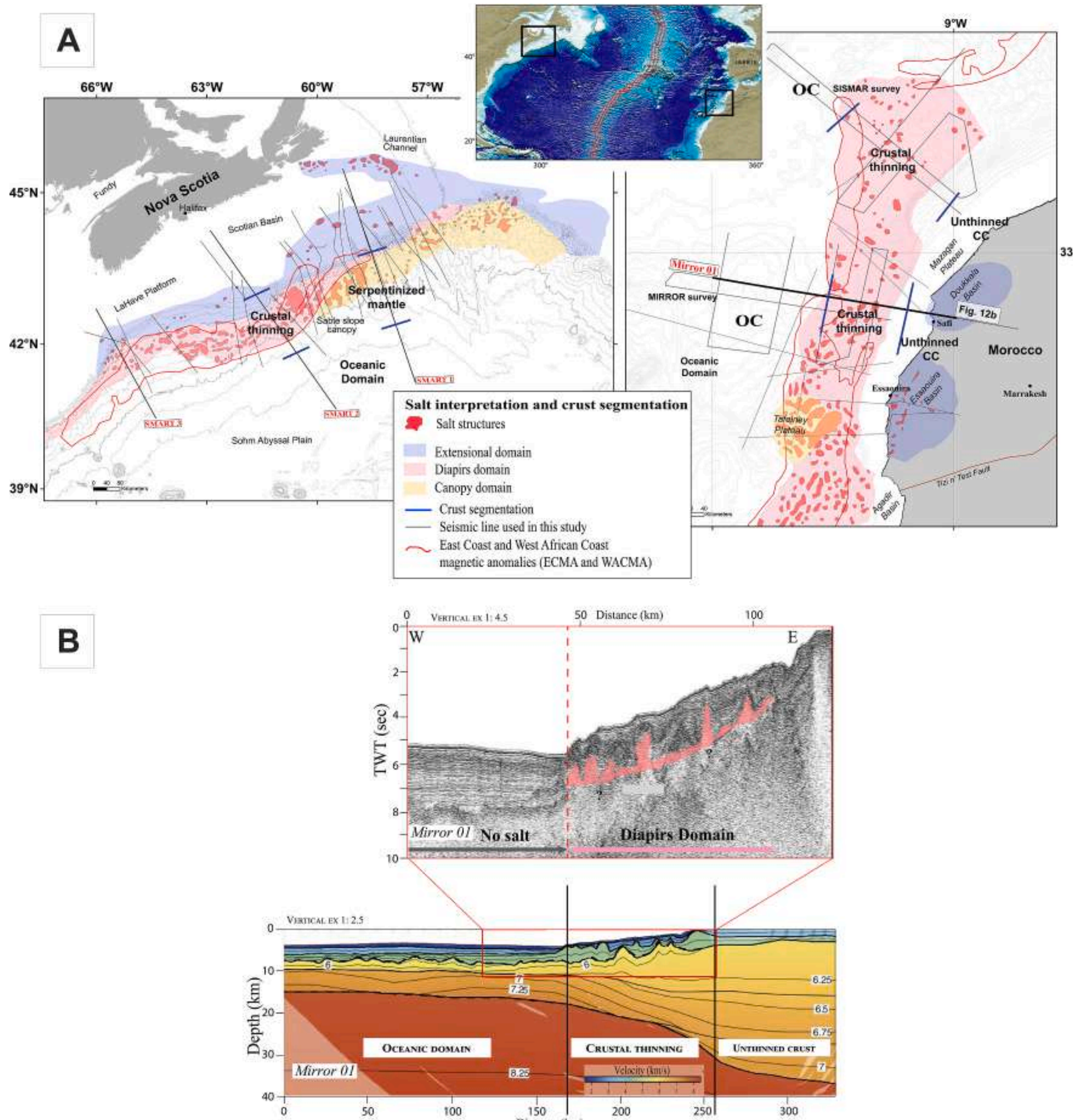


Fig. 12. Map showing salt morphologies and crustal segmentation in Nova Scotia and Morocco conjugated margins. Crust segmentation is taken from SMART, SISMAR and MIRROR refraction studies (references in the text). Salt structures are from Shimeld (2004); Sahabi (2004) and Tari et al. (2000). Black lines represent the seismic profile, interpreted in this study (references in the text). Canopy (allochthonous) salt in Nova Scotia is from Sahabi et al. (2004) interpretation. (B) Mirror01 reflection and wide-angle associated profiles (location in Fig. 12a). Modified after Biari et al. (2015). Dashed black lines represent the lower and upper limit of the crust.

domain in the proximal sag basin, characterized by salt stocks, weld structures and wide pillows. In the Canopy-Massive domain, as in the Santos basin, the salt is thick, stands above the sag basin and the base of salt is hampered. It can extend over the oceanic crust, forming nappe geometries (Fig. 10). Whatever the crustal nature of the different segments in the transitional domain, there is a strong coincidence between: 1) crustal domain T1 and the overlaying Large Diapir Domain, 2) crustal domain T2 and the Canopy-Massive Salt domain (Fig. 10b). In the Santos and Angolan margin, the limit between the Diapir domain to the Massive-Canopy domain corresponds to a shallower Moho depth (from ~20 km to ~15 km) and a thinning of crust (from ~12-15 to ~5-8 km).

In the Gulf of Mexico, the crustal segmentation incertitude (Fig. 11) and the wide spatial distribution of salt structures make it difficult to compare crustal nature and salt morphologies. Nevertheless, the canopy structures in the Sigsbee Escarpment lays on extremely thinned transitional crust, probably exhumed (Rowan, 2014, 2018), and on oceanic crust. The crust below the wide canopy domain thins (up to 8 km) and the Moho rises and could be characterized by mantle exhumation (Rowan, 2014).

The salt tectonics system of Morocco-Nova Scotia conjugated margins exhibits some differences with respect to the Gulf of Mexico and South Atlantic margins. The Diapir salt domain is mainly centred on the Necking Zone domain, where the crust is of continental nature and thinned (Fig. 12; Biari et al., 2015) and the deformation is affected by the initial salt thickness and the underlying basement structures (Ings and Shimeld, 2006; Krézsek et al., 2007). The Massive-Canopy salt domain occupies a vast area only in the Nova Scotia margin and is characterized by salt derived from the Diapir Domain, which glided towards the deep basin after its deposition (Sahabi et al., 2004) (Fig. 12). In the Moroccan margin, the seaward movement is limited (Holik et al., 1991), except in the Tafelney Plateau (Fig. 12), where some salt canopies may have locally mobilized over a distance of up to 20 km.

The correlation between salt morphology and crustal segmentation in the different basins suggests that Canopy/Massive salt domains are associated with crustal domains that have undergone magmatic intrusions at their base (highly intruded exhumed lower continental crust, as in Angola Basin) or proto-oceanic to oceanic domain (Provençal Basin, Santos Basin). Concomitant to this salt domain, the Moho is shallower and the crust thinner.

In contrast to the Western Mediterranean Sea, several mechanisms may be at the root of the crustal segmentation-salt morphology coincidence. The salt passive margin segmentation caused by the interaction of gliding-spreading mechanisms (e.g. Ge et al., 1997; Vendeville, 2005; Hudec and Jackson, 2007; Gaullier et al., 2006; Brun and Fort, 2011; Rowan et al., 2012) likely explains the downdip succession of salt morphologies domains but does not fully demonstrate their spatial coincidence with crustal domains. The present-day salt structure distribution could be related to the salt deposition timing with respect to rifting phases (Jackson et al., 1994; Tari et al., 2003; Rowan, 2014, 2018; Jackson and Hudec, 2017; Hudec and Peel, 2019). The crustal structure controls the topography at the time of salt deposition and thus exerts a primary control on initial salt thickness. The salt thickness can govern the evolution of salt morphologies, which result from, among other causes, the salt supply (e.g. Hudec and Jackson, 2007). A good example are the Morocco-Nova Scotia conjugated margins, considered as syn-rift (Tari et al., 2003; Tari et al., 2012) or syn-stretching (Rowan, 2014) salt basins. Here, the salt was deposited during the last stage of rifting, prior to the breakup, in the Upper Triassic/Lower Jurassic (Hafid, 2000; Tari et al., 2003). The salt structures are thus attributed to the underlying basement structure, which determined the initial configuration of the basins and influenced the initial salt thickness (Ings and Shimeld, 2006; Krézsek et al., 2007). In the Gulf of Mexico and South Atlantic salt basins, several authors claimed significant variations in initial salt thickness (Gulf of Mexico: Rowan, 2014, 2018; Hudec et al., 2013a) while others (Angolan margin: Moulin et al., 2005) a roughly constant thickness and no post-deposition horizontal movements. Consequentially, the salt deposition context, as well as its impact on present-day salt structures is still debated.

9. Conclusion

We have shown that due to the specific features in the Western Mediterranean, the classic salt tectonics models fail to explain the regional differences in salt morphology distribution, early deformation in the deep basin and spatial coincidence with crustal segmentation.

A different temperature distribution at the base of salt related to fluids and/or heat segmentation resulting from different crustal natures could play a part, affecting salt rheology and thus adding a further component to the already well-known mechanisms.

The same coincidence is observed in some global salt-bearing passive margins. Although the discussion on the main mechanisms of salt tectonics in passive margins remains open, the heat segmentation hypothesis should not be overlooked and warrants further investigation, especially in view of the evidences observed in the Western Mediterranean Sea.

Further heat flow analyses are needed to correlate salt-deformation timing with the thermal regime evolution in passive margins. Moreover, analogue and/or numerical modelling might be useful to isolate the temperature parameter impact and understand how the salt may change morphology and timing with a different temperature regime at its base.

Contributions

The study was conceived by DA. MB has re-interpreted and compiled the different salt morphologies with the help of RP, DA, MM, MR, EL, CG, ADB. The compilation and analysis of the published wide-angle data were done by MB, MM, DA. The thermal data were provided by JP. AC provided new seismic data. All authors provided critical feedback and helped shape the research, analysis and manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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