



## **Tectonic and stratigraphic evolution of the Western Alboran Sea Basin in the last 25 Myrs**

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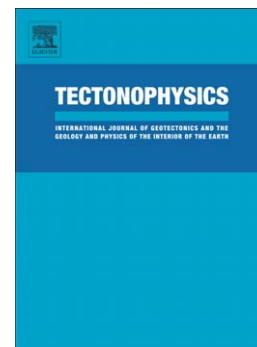
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# Tectonic and stratigraphic evolution of the Western Alboran Sea Basin in the last 25 Myrs

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## 1. Abstract

The Western Alboran Basin (WAB) formation has always been the subject of debate and considered either as a back-arc or a forearc basin. Stratigraphic analyses of high-resolution 2D seismic profiles mostly located offshore Morocco, enabled us to clarify the tectonic and stratigraphic history of the WAB. The thick pre-rift sequence located beneath the Miocene basin is interpreted as the topmost Malaguide/Ghomaride complex composing the Alboran domain. The structural position of this unit compared with the HP-LT exhumed Alpujarride/Sebtide metamorphic basement, leads us to link the Early Miocene subsidence of the basin with an extensional detachment. Above the Early Miocene, a thick Serravallian sequence marked by siliciclastic deposits is nearly devoid of extensional structures.

Its overall landward to basinward onlap geometry indicates that the WAB has behaved as a sag basin during most of its evolution from the Serravallian to the late Tortonian. Tectonic reconstructions in map view and in cross section further suggest that the basin has always represented a strongly subsiding topographic low without internal deformation that migrated westward together with the retreating slab. We propose that the subsidence of the WAB was controlled by the pull of the dipping subducting lithosphere hence explaining the considerable thickness (10 km) of the mostly undeformed sedimentary infill.

## 2. Introduction

Post-Eocene Mediterranean geodynamics is governed by the northward subduction of the African plate and coeval slab retreat causing the formation of back-arc basins together with extension and collapse of internal zones of orogens (Réhault *et al.*, 1984; Malinverno and Ryan, 1986; Dewey, 1988; Royden, 1993; Wortel and Spakman, 2000; Jolivet and Faccenna, 2000; Faccenna *et al.*, 2001) after a major change in the subduction regime during the Oligocene (Faccenna *et al.*, 1997; Jolivet and Faccenna, 2000). The present-day complex geometry of these subduction zones results from progressive slab tearing and detachment (Carminati *et al.* 1998a, 1998b, Wortel and Spakman, 2000) associated with a complex 3D mantle convection pattern (Faccenna *et al.*, 2004; Spakman and Wortel, 2004; Jolivet *et al.*, 2009, 2013; Faccenna and Becker, 2010; Sternai *et al.*, 2014).

In the western Mediterranean, several back-arc basins have opened since the Oligocene following the retreat of the Tethyan slabs: the Liguro-Provençal basin, Algerian basin, Alboran Sea and Tyrrhenian Sea (Fig. 1, Faccenna *et al.*, 2001). Amongst these basins, the Alboran Sea basin remains one of the most controversial issues in western Mediterranean geodynamics. Several hypotheses have been proposed so far to explain its formation by extension in the internal zones of the Betics-Rif orocline: (1) extensional collapse of a thickened crust due to convective removal of the continental lithospheric mantle (Platt and Vissers, 1989; Platt *et al.*, 2003a) or (2) a delamination process (Seber *et al.*, 1996; Calvert *et al.*, 2000) or (3) the westward retreat of the subduction zone (Royden, 1993; Lonergan and White, 1997; Gutscher *et al.*, 2002). Several authors pointed to the relation linking the behavior of Mediterranean slabs in the upper mantle and the tectonic history recorded in the crust (Faccenna *et al.*, 2004; Spakman and Wortel, 2004; Jolivet *et al.*, 2006, 2008; Booth-Rea *et al.*, 2007). In more detail, the stretching of the continental crust composing back-arc regions appears to follow the mantle stretching during slab retreat (Jolivet *et al.*, 2009), suggesting that back-arc extension was partly driven from below (Sternai *et al.*, 2014).

The Alboran domain represents the westernmost termination of the peri-Mediterranean Alpine belt orogeny. Its arcuate shape, delimited by the Betic and Rif fold-and-thrust belts, is the result of

subduction, collision and slab migration processes that mainly occurred during the Miocene (Faccenna *et al.*, 2004; Spakman and Wortel, 2004; Jolivet *et al.*, 2008). During the Neogene, several sedimentary basins were formed on top of the Alboran metamorphic basement. The thickest and oldest sedimentary depocenter, the Western Alboran Basin (WAB; Fig. 2A), was created and developed coeval with the exhumation and denudation of its underlying metamorphic continental crust (Soto *et al.*, 1996; Comas *et al.*, 1999). Different views of the basin fill geometry over time led to a variety of tectonic scenarios for the WAB inception: a pull-apart mechanism in a regional strike-slip setting (Bourgois *et al.*, 1992), a sag basin (Morley, 1992, 1993) or a half-graben asymmetric basin (Mauffret *et al.*, 2007).

The aim of this paper is to re-assess the architectural evolution of the Western Alboran Basin in relation to major geodynamic events through a comprehensive seismic analysis of the most complete dataset of seismic profiles available in the area (Fig. 2B). We then correlate this new tectonostratigraphic framework of the WAB with the onshore stratigraphic sequence and tectonic data covering both southern Spain and northern Morocco, with a more specific view from the Moroccan margin. Our final objective is to propose a coherent geodynamic model for the formation and evolution of the WAB based on our observations but also on the vast amount of information available on the surroundings, especially regarding the tectonic and sedimentary history of the peri-Alboran sedimentary basins.

Following up on this new set of observations at the scale of the whole basin, we illustrate the tectonic evolution with a series of palaeogeographic reconstructions and discuss the possible causes of the rapid subsidence and weak deformation observed on the Moroccan margin. We show that the evolution of the WAB was first controlled by a regional extensional phase in the Early Miocene, followed by a period of quiet tectonics and intense sedimentation and rapid subsidence in the Middle Miocene. The Western Alboran Basin subsidence most likely migrated hundreds of kilometers westward without significant deformation above a retreating slab and its subsidence may be due to the persisting density anomaly of the underlying dipping slab.

### 3. Geological settings and tectonic framework

#### 3.1. Western Mediterranean geodynamic models and mantle structures

The complexity of the Betic–Rif orogenic system led to different types of geodynamic reconstructions that are still debated today (Lonergan and White, 1997; Jolivet *et al.*, 2009; Vergés and Fernández, 2012; Platt *et al.*, 2013). Most propose subduction models involving slab roll-back, delamination, slab break-off or slab tearing (Royden, 1993; Lonergan and White, 1997; Gueguen *et al.*, 1998; Calvert *et al.*, 2000; Rosenbaum *et al.*, 2002a; Faccenna *et al.*, 2004; Spakman and Wortel,

2004; Jolivet *et al.*, 2006, 2008; Vergés and Fernàndez, 2012). In the past few years, based on tomographic imagery, the analysis of mantle seismic anisotropy and modeling, a rather consensual model has emerged of the presence of a E-SE dipping slab beneath the Gibraltar-Betics area and retreating westward (Wortel and Spakman, 2000; Spakman and Wortel, 2004; Levander *et al.*, 2014; Thurner *et al.*, 2014).

Tomographic studies revealed the presence of an arcuate, vertical high-velocity anomaly located beneath the western Alboran Sea and southern Spain (Gutscher *et al.*, 2002; Faccenna *et al.*, 2004; Spakman and Wortel, 2004; Bezada *et al.*, 2013). This anomaly, which has been interpreted as a remnant of the Alpine Tethys slab, extends continuously from a depth of 50 km to a depth of more than 600 km (Bezada *et al.*, 2013). It is curved below the Gibraltar Arc and is partially detached from the surface below the eastern Betics (Spakman and Wortel, 2004; Bezada *et al.*, 2013).

The Alboran area is affected by a large amount of shallow to intermediate- depth seismicity (40-120 km; Gutscher *et al.*, 2002; Bufo *et al.*, 2004; Stich *et al.*, 2006; Pedrera *et al.*, 2011; Ruiz-Constán *et al.*, 2011; Mancilla *et al.*, 2013) and rare deep earthquakes (>600 km; Bufo *et al.*, 1997). The intermediate-depth seismicity is clustered along a ~N-S trend beneath the Western Alboran Basin (Fig. 3A). This seismicity is aligned along the subducting plate curvature at the depth where the subducting slab starts to sink vertically (Fig. 3A; Bezada *et al.*, 2013) and where mantle stresses produce a down-dip extension in the external arc of the continental slab (Ruiz-Constán *et al.*, 2011). It is worth noting that the Western Alboran Basin (e.g. the main sedimentary depocenter of the area) is located above the slab hinge (cross-sections in Fig. 3A).

### **3.2. The Betic-Rif orogenic system in the Alpine belt**

The Betic-Rif system results from the continental collision between the Alboran domain and the former Iberian and African passive margin during the Miocene (García-Hernández *et al.*, 1980; Platt *et al.*, 2003a; Chalouan *et al.*, 2006; Crespo-Blanc and Frizon de Lamotte, 2006). In reality, this widely accepted scheme might be more complex than originally thought, as a possible suture zone was recently described within the external Rif (Michard *et al.*, 2014). Simultaneously, the Internal zones, also referred to as the Alboran domain, underwent an extension of their metamorphic basement (Platt and Vissers, 1989; García-Dueñas *et al.*, 1992; Augier *et al.*, 2005a, b). From the external toward the internal zones, the Betic-Rif realm is composed of several tectonic domains (Fig. 1, 2A): (a) two foreland basins, namely the Guadalquivir and the Gharb basins; (b) the External Zones of the Betics and Rif; (c) the Flysch Trough units; (d) the metamorphic complexes of the Internal Zones and (e) the Alboran Sea basins.

The former Iberian and African passive margins compose fold-and-thrust belts called the

External Zones (Fig. 2A), following the Gibraltar Arc. Made up of Mesozoic and Cenozoic deposits, these units overthrust both the Iberian and Moroccan continental basements, during the late Eocene and Miocene, respectively (García-Hernández *et al.*, 1980; Wildi, 1983; Berástegui *et al.*, 1998; Frizon de Lamotte *et al.*, 2004). Two foreland basins were formed during overthrusting of the External Zones, the Guadalquivir basin (north of the Betic Cordillera) and the Gharb basin (south of the Rif) (Fig. 1). Both basins display a rather similar Middle Miocene (Langhian) to Pliocene sequence (Flinch, 1994; Berástegui *et al.*, 1998; Fernández *et al.*, 1998; Vera, 2000; Chalouan *et al.*, 2008). In the Gulf of Cadiz, a thick chaotic body observed in seismic reflection imaging and called the Imbricate Wedge (Iribarren *et al.*, 2007) comprises a west-migrating thrust system correlated with two chaotic units in the Guadalquivir and Gharb basins (Maldonado *et al.*, 1999; Iribarren *et al.*, 2007).

The Flysch Trough units (or Flysch Complex) are structurally sandwiched between the External and Internal Zones (Fig. 1, 3). These deep siliclastics sediments are composed of four main units on both sides of the Strait of Gibraltar, and were mostly deposited from the upper Cretaceous to the lower Miocene (Didon *et al.*, 1973; Guerrero *et al.*, 1993).

The Internal Zones of the Betic and Rif orogenic belt, also referred to as the Alboran domain, are composed of three metamorphic complexes stacked during the Alpine orogeny. From bottom to top, the Internal Zones are composed of the Nevado-Filabride (NFC), the Alpujarride/Sebtide (ASC) and the Malaguide/Ghomaride (MGC) complexes (Fig. 2A; Torres-Roldán, 1979; Martínez-Martínez and Azañón, 1997; Michard *et al.*, 2002). Located between the Malaguide/Ghomaride complex and the Flysch units, the Mesozoic-Paleogene Dorsale Calcaire represents the sedimentary cover of the inner Alboran domain (Chalouan and Michard, 2004; El Kadiri *et al.*, 2006). Nevado-Filabride and Alpujarride/Sebtide complexes underwent a high-pressure (HP) and low-temperature (LT) metamorphism (Puga *et al.*, 2000; López Sánchez-Vizcaíno *et al.*, 2001; Martínez-Martínez *et al.*, 2002a; Augier *et al.*, 2005a). The age of the HP-LT event is not well established for either complex: (a) it extends from the Early Eocene (Monié and Chopin, 1991), Oligocene (Augier *et al.*, 2005b) to as late as the Middle Miocene (López Sánchez-Vizcaíno *et al.*, 2001; de Jong, 2003; Platt *et al.*, 2006) for the Nevado-Filabride complex; (b) and from the Early Eocene to the Oligocene for the Alpujarride/Sebtide complex (Monié and Chopin, 1991; Platt *et al.*, 2005; Michard *et al.*, 2006). Today, the three Nevado-Filabride, Alpujarride/Sebtide and Malaguide/Ghomaride complexes are separated by crustal-scale extensional shear zones (García-Dueñas *et al.*, 1992; Lonergan and Platt, 1995; Platt *et al.*, 2005; Augier *et al.*, 2005a). The exhumation of the Alpujarride/Sebtide complex occurred during the Early Miocene (22 to 18 Ma) in a N-S to NNE-SSW extensional setting (Monié *et al.*, 1994; Crespo-Blanc *et al.*, 1994; Crespo-Blanc, 1995; Kelley and Platt, 1999; Platt *et al.*, 2005) while the exhumation of the Nevado-Filabride complex occurred from the Early to the late Miocene (20 to 9 Ma; de Jong, 1991; Monié and Chopin, 1991; Johnson *et al.*, 1997; Augier *et al.*, 2005b; Platt *et al.*, 2005; Vázquez *et al.*, 2011) through a ~E-W regional-scale extension (Jabaloy *et al.*, 1992).

Two large bodies of mantle peridotites were found both in Spain (Ronda) and in Morocco (Beni Bousera). These bodies were emplaced in the Alpujarride/Sebtide complex at around 22 Ma (Esteban *et al.*, 2011) through a basal crustal south-verging thrust (Hidas *et al.*, 2013; Précigout *et al.*, 2013).

### **3.3. Peri-Alboran sedimentary basins**

From the Early Miocene onward, compressive deformation progressively propagated through the Betic and Rif External Zones (Crespo-Blanc and Frizon de Lamotte, 2006) while extension and erosion occurred in the Internal Zones. As a consequence, two main generations of sedimentary basins were formed. The first subsidence pulse took place early in the Aquitanian-Burdigalian up to Langhian time while the second occurred later during the Serravallian-Tortonian (Sanz de Galdeano and Vera, 1992; Vissers *et al.*, 1995; Vera, 2000). The first generation of basins is currently highly tectonised and their initial geometry is difficult to reconstruct as their outcrops progressively disappear from the west to the east of the Betic Cordillera (Serrano *et al.*, 2007). They are almost absent in the Internal Rif (Serrano *et al.*, 2007). This first generation of sedimentary basins lies unconformably over the Malaguide-Alpujarride basement and is associated with E-W trending, generally top-to-the-N extensional structures (Crespo-Blanc *et al.*, 1995; Serrano *et al.*, 2007; Suades and Crespo-Blanc, 2013). The second generation of sedimentary basins formed from the Serravallian onward (Sanz de Galdeano and Vera, 1992; Vera, 2000; Rodríguez-Fernández *et al.*, 2011), under a top-to-the-WSW extensional regime. These basins, also called intramontane basins, are mostly located in the southeastern Betics and are composed of a similar stratigraphic succession (Rodríguez-Fernández *et al.*, 2011). Extensional structures were observed at the border of the basins or within the earlier deposits leading some authors to link their initiation with the latest exhumation stages of the Nevado-Filábride complex (Crespo-Blanc, 1995; Meijninger and Vissers, 2006; Rodríguez-Fernández and Sanz de Galdeano, 2006; Augier *et al.*, 2013; Do Couto *et al.*, 2014b).

### **3.4. Structure and stratigraphy of the Western Alboran Basin**

#### **3.4.1 Basin floor**

The crustal structure of the Alboran Sea shows an abrupt thinning, starting from the Betic and Rif Chains (~45 km) toward the Alboran Sea (~15-20 km) (Fig. 3.B; Fullea Urchutegui *et al.*, 2005; Turner *et al.*, 2014). The Alboran Sea basement is composed of metamorphic rocks similar to those found in the Internal zone of the Betic Cordillera (Sánchez-Gómez *et al.*, 1999; Soto *et al.*, 1999) intruded by many volcanic seamounts aged between 17 to 8 Ma (Comas *et al.*, 1999; Duggen *et al.*,

2008). Radiometric ages of the Alpujarride-Sebtide basement drilled at the ODP Site 976 suggested exhumation in the Early Miocene, between 20 and 18 Ma (Kelley and Platt, 1999; Hurford *et al.*, 1999). These ages of exhumation agree with the exhumation history of the Alpujarride-Sebtide metamorphic nappe, outcropping both in the Betics and Rif Chains, which progressively exhumed in a roughly N-S extensional setting (Monié *et al.*, 1994; Crespo-Blanc *et al.*, 1994; Crespo-Blanc, 1995; Platt *et al.*, 2003b, 2005; Michard *et al.*, 2006; Chalouan *et al.*, 2008).

It is widely accepted that the Alboran Basin was concerned by extensional tectonics from the Early to the late Miocene followed by a contractional reorganization resulting from the convergence of the Eurasian and African plates (Comas *et al.*, 1999). This late Miocene and still ongoing compression resulted in the inversion of the Alboran Ridge up to the Xauen Bank (Bourgois *et al.*, 1992; Chalouan *et al.*, 1997).

### 3.4.2 Stratigraphy of the WAB

The history of the Alboran Sea was mainly explored in the 1980s with the drilling of five commercial wells on both the Spanish and Moroccan upper slopes (Andalucia-A1 and G1, Alboran A1, El Jehba, Nador 1; Fig. 2A) accompanied by the acquisition of a dense grid of two-dimensional (2-D) multichannel seismic profiles (>10,000 km). Several studies presented the main results of these seismic surveys offshore Spain and Morocco (Bourgois *et al.*, 1992; Comas *et al.*, 1992; Mauffret *et al.*, 1992; Morley, 1992, 1993; Chalouan *et al.*, 1997; Booth-Rea *et al.*, 2007). More recently, up to 3,000 km of high-resolution 2-D multichannel seismic profiles were acquired on the WAB (Fig. 2B). Part of this recent 2D seismic dataset was presented by Soto *et al.* (2010) who studied shale tectonics on the Spanish side of the Alboran Sea. Kuo *et al.* (2002), Mountfield *et al.* (2002), and Weinzapfel *et al.* (2003) reassessed and specified the hydrocarbon potential of the Alboran Sea arguing in favor of a Miocene petroleum system in this basin.

Several academic cruises (Willet, 1991; Maldonado *et al.*, 1992; Watts *et al.*, 1993), industrial seismic surveys (Bourgois *et al.*, 1992; Comas *et al.*, 1992; Morley, 1992; Chalouan *et al.*, 1997), and analyses of boreholes (Jurado and Comas, 1992) revealed the overall Alboran Sea structure and infilling. Three main subbasins, called respectively the Western, Southern and Eastern Alboran Basins (WAB, SAB, EAB; Fig. 2A) rest on the metamorphic and volcanic basement. The most important sedimentary depocenter is located on the Western Alboran Basin (WAB) and its axis mimics the arcuate geometry of the orogenic arc (Soto *et al.*, 1996; Iribarren *et al.*, 2009). The sedimentary thickness of the WAB is estimated at between 10 to 12 km (Soto *et al.*, 1996; Mauffret *et al.*, 2007; Iribarren *et al.*, 2009; Weinzapfel *et al.*, 2003) and is mainly affected by shale tectonics (Soto *et al.*, 2010) and associated mud volcanism (Pérez-Belzuz *et al.*, 1997; Sautkin *et al.*, 2003; Blinova *et al.*, 2011; Somoza *et al.*, 2012; Gennari *et al.*, 2013). Three wells, called Alboran-A1, Andalucia-G1 and

El Jebha, located on the Spanish and Moroccan shelves (Fig. 2A), enabled recovery of a stratigraphic column mainly composed of siliciclastic layers from the Lower Miocene to the Quaternary (Jurado and Comas, 1992; Morley, 1992; Chalouan *et al.*, 1997). Previous studies provided a general chronostratigraphic framework of the sedimentary filling of this basin and defined up to six major seismic units (unit I to unit VI) (Fig. 4; Comas *et al.*, 1992; Jurado and Comas, 1992; Comas *et al.*, 1999, Soto *et al.*, 2010, Hernández-Molina *et al.*, 2011) separated by regional unconformities. From bottom to top:

- Unit VI (latest Aquitanian? - Burdigalian) is composed of clays with interbedded sandy intervals above a basal pebbly sandstone. This interval was drilled in the Alboran-A1 well and logging data suggested the occurrence of undercompacted shales. It consists of olistostromes containing polymictic rocks (olistoliths and rock breccia) embedded in an undercompacted shale matrix.

- Unit V (Langhian - Lower Serravallian) is separated into two sub-units: the lower subunit, Vb, is made up of clays, interbedded silty to sandy clays, and a basal coarse-grained sandstone. Recorded in the Andalusia-G1 and Alboran-A1 wells, this unit displays typical features of undercompaction with abnormal pressures. The upper subunit, Va, consists of well-graded sand-silt-clay turbidites and turbiditic muds interbedded with volcanogenic layers.

- Unit IV (Serravallian – Tortonian) consists of graded sand-silt-clay turbidites interbedded with a few volcanogenic layers.

- Unit III (Upper Tortonian) is composed of sandstone intervals, with claystones and silty clay beds, also corresponding to turbidite facies with some channel-like features.

- Unit II (Messinian) consists of marine sandy turbidites interbedded with carbonates, and volcanoclastics layers. The upper section is made of gypsum and thin anhydrite intervals linked to the Messinian Salinity Crisis deposits.

- Unit I (Pliocene – Quaternary) is represented by pelagic and hemipelagic marls and clays, muddy to sandy turbidites, and contouritic deposits.

The undercompacted shales in unit VI and sub-unit Vb are involved in the mud volcanic activity of the area (Sautkin *et al.*, 2003; Gennari *et al.*, 2013) and in the shale tectonics that affect the WAB (Chalouan *et al.*, 1997; Soto *et al.*, 2010).

## 4. Datasets and methodology

Within the study area, the seismic dataset comprises 10,000 km of vintage 2D seismic lines covering the entire WAB through the Gibraltar Arc (Fig. 2B). The mean seismic data coverage

fluctuates between 5 and 7 seconds two-way travel time (TWTT) revealing a thick Neogene cover above the metamorphic basement even though the base of the sedimentary depocenter is barely perceptible in the deepest parts. An additional 2,500 km of 2D seismic lines acquired by Conoco in 2000 and 2001 (CAB survey) were used (courtesy of the ONHYM Morocco and the ICM-CSIC of Barcelona). This seismic dataset covers as deep as 12 seconds TWTT and makes it possible to investigate the deeper units in the WAB in more detail. All the seismic profiles, including the CAB surveys both offshore Spain and Morocco (orange lines in Figure 2B) are available in two-way travel time (TWTT). In addition, the CAB seismic lines located offshore Spain are also accessible in the depth domain (migrated by Conoco with stacked and root-mean square velocities inversion; blue lines in Figure 2B).

We conducted a detailed study of all 12,500 km of seismic data to characterize and define the seismic unit architecture of the Western Alboran Basin together with the geometry of their bounding surfaces (onlap, toplap, downlap and truncations) based on the seismic stratigraphic principles presented by Mitchum and Vail (1977), Van Wagoner *et al.* (1988) summarized in Catuneanu *et al.* (2009). The seismic stratigraphic analysis was performed on all the TWTT seismic profiles and jointly propagated on the depth migrated seismic lines of the CAB dataset offshore Spain by recognition of the seismic units (thanks to their respective facies and stratal terminations). The depth migrated CAB seismic lines were generated to match the geological interfaces encountered in the deep wells and to better represent the geometry of the basin fill. For this reason, and also to illustrate the complete seismic dataset, seismic profiles of the CAB dataset are displayed in the time domain offshore Morocco and in the depth domain offshore Spain.

Isochron maps of the main stratigraphic sequences were generated and converted into isochore and then into isopach maps using average seismic velocities calculated from the sonic log velocities recorded in the Andalucia-G1 and El Jebha wells (Chalouan *et al.*, 1997; Soto *et al.*, 2010). During this process, the depth migrated seismic profiles (offshore Spain) helped check the consistency of the calculated isopach. Isopach maps of the main stratigraphic sequences identified provide important information about the migration of depocenters and the deformation history of the WAB over time. The seismic units identified in the 2D seismic dataset were tied to the Andalucia-G1 and El Jebha wells (Figs. 4, 5, 6). Isopach maps were then computed for each seismic unit to identify growth-related, thinning and subsidence thickening units in order to constrain the evolution of the basin over time.

Among all the foraminifers and calcareous nannoplankton species recognized in both wells, biostratigraphic markers (listed in the middle column in Figure 4) helped to reassess the ages of the formations according to Neogene standard zonations (Lourens, 2004; Raffi *et al.*, 2006; Anthonissen and Ogg, 2012; Hilgen *et al.*, 2012). The Pliocene in the Andalucia-G1 well is characterized by the

basal occurrence of the *Sphaeroidinellopsis* acme zone and the first occurrence of *G. margaritae* from 860 m upward. The Messinian can be delineated by the co-occurrence of *G. plesiotumida* and *G. miotumida* (*conomieza*). The limit between the Tortonian and the Serravallian remains less clear, it was set after the last occurrence of *G. praemenardii* (at 1,934.8 m) and before the first occurrence of *G. dehiscens* and *G. menardii cultrata* (at 1,920 m). Likewise, the boundary between the Serravallian and the Langhian was set after the last occurrence of *P. glomerosa* (at 3,040 m) and before the first occurrence of *G. mayeri* and *G. siakensis* (at 3,020 m). The base of the well is marked by the occurrence of *Praeorbulina sicana*, which characterizes the late Burdigalian-Early Langhian (occurrence from 16.38 to 14.53 Ma; Anthonissen and Ogg, 2012).

In the El Jebha well, the Pliocene and Messinian biozones are respectively marked by the occurrence of *G. margaritae* and *D. quinquaramus* (Fig. 4). The co-occurrence of *G. acostaensis*, *G. menardii* and *D. quinquaramus* between 420.6 and 1,993.4 m identifies the Tortonian but the boundaries between the Langhian, Serravallian and Tortonian are not clear.

To place the formation and evolution of the WAB in the westernmost Mediterranean geodynamic context, we generated several paleogeographic maps at regional scale. These reconstructions were created from the paleokinematic reconstructions of Jolivet *et al.* (2006), which, in turn, are based on the kinematic parameters of Dewey *et al.* (1989) and concerning motion of large plates, on Rosenbaum *et al.* (2002b). Paleo-coastlines came from several different sources (Dercourt *et al.*, 1993; Meulenkamp and Sissingh, 2003; Gibert *et al.*, 2013) and were adapted based on our own observations (Do Couto *et al.*, 2014a, b) in the knowledge that the more recent the reconstructed paleo-coastlines, the more accurate their contours.

## 5. Seismic stratigraphy: results and interpretation

### 5.1. Seismic stratigraphic interpretation

To define seismic units, we conducted seismic stratigraphic analysis of several recently acquired seismic profiles, beginning with the Spanish margin where the CAB01-125, devoid of any shale tectonic perturbation (Fig. 5), enables interpretation of up to 11 horizons (referred to as R1-R8, from the oldest to the youngest) that can be traced over long distances. In between, eight major seismic units (SU) are defined by their seismic facies, large-scale reflection configurations and their specific stratigraphic contacts with their lower and upper bounding surfaces. The boundaries that delimit the seismic units are marked by stratal terminations and sometimes by an acoustic impedance jump, either positive or negative depending on the acceleration or deceleration of the acoustic velocity. All horizons and seismic units in between were tied to the Andalusia-G1 and El Jebha wells, as shown in Figure 4. We now describe the seismic units from bottom to top.

### 5.1.1. SU1

**Description** - The deepest seismic unit, SU1 (Fig. 5, 6), is characterized by a moderate to high amplitude, a discontinuous reflection package in the basin as well as minor chaotic internal reflections (Fig. 6). On the Spanish side, SU1 reflection packages onlap a high-amplitude reflector R1 (Fig. 5), defining the top of the acoustic basement. This unconformity can be traced all round the basin even if it is difficult to recognize in the deepest part because tectonic activity and mobile shale disturb the signal. Where it is visible, its upper bounding surface R2 is marked by erosional truncation of SU1 reflectors and onlap or baselap terminations of the younger sequences (Fig. 5, 7).

On the eastern Moroccan margin, SU1 is thick (~ 2s TWTT) and is composed of two main subunits called SU1a and SU1b (Fig. 8). The lower bounding surface of SU1a is characterized by a high amplitude reflector that appears to be disrupted by several normal faults, whereas the top one corresponds to a major onlapping surface (Fig. 8). The upper subunit (SU1b), which is similar to that identified offshore Spain, is marked by moderate to high-amplitude and discontinuous reflectors with more chaotic reflections locally (Fig. 8). The lower subunit (SU1a) presents low to moderate amplitude reflectors together with chaotic internal reflections and is separated from SU1b by a high amplitude disrupted reflector. SU1a disappears toward the east and south of the WAB, and SU1b lies directly on the acoustic basement (Fig. 8, 9) as observed offshore Spain (Fig. 5, 7). Two SW-NE dip seismic lines display the wedge-shape configuration of the entire SU1 together with progressive thinning of SU1a toward the center of the basin (Fig. 10, 11). A close-up of the seismic attributes of SU1 on the Moroccan margin (CAB01-140 in Figure 12) shows that the base of subunit SU1b is relatively well marked by a high amplitude, red-to-blue couple of reflectors. To the south, SU1b is deformed by prominent thrusts (Fig. 8, 9), probably rooted in the basement, and marking the frontal thrust of the Xauen Bank (Fig. 1). In addition, R1 reflector (top of the acoustic basement) appears discontinuous and deformed in the center of the WAB, suggesting a deformation phase and hence the basement (thick-skin deformation). The alignment and offset of the structures suggest the presence of a central transpressional zone that will be discussed later in conjunction with the basin fill geometry.

**Interpretation** - This seismic unit has never been drilled in the Alboran Sea. Chalouan *et al.* (1997) interpreted this tilted unit as belonging to the Middle Miocene, whereas Mauffret *et al.* (2007) interpreted it as belonging to the deepest Lower Miocene unit VI drilled offshore Malaga (e.g. Comas *et al.*, 1999). Its age and significance thus remain questionable and will be addressed later on. The seismic facies of this unit is mainly composed of moderate to high amplitude reflectors that are strongly deformed on the northern Moroccan margin (Fig. 8), and evolve laterally to a lower amplitude and more chaotic facies (Fig. 10). In the deepest part of the basin, sub-unit SU1b is characterized by a cohesive package of high amplitude subparallel reflectors (Fig. 11). The acoustic facies is clearly of sedimentary origin in this profile and could reflect the presence of carbonate beds or siliciclastic deposits like condensed turbiditic layers. The tilted geometry of SU1 unit together with

its onlapping upper bounding surface suggest a deposition preceding the main subsidence and rifting phases of the Western Alboran Basin. In the southern part of the WAB, SU1 is tilted all along the margin and can be traced landward (Fig. 8).

### 5.1.2. SU2

**Description** – SU2 is separated from SU1 by a high-amplitude low-frequency continuous reflector R2 (Fig. 5). SU2 is dominated by moderate to high-amplitude and low-frequency semi-continuous reflection packages that are extensively deformed. The stratigraphic contacts of this unit are characterized by onlap terminations on the acoustic basement toward the center of the basin, and by baselap termination on R2 reflector (Fig. 5, 7, 11). SU2 is relatively thin, never exceeding 300 m on the depth migrated seismic line and its spatial distribution is limited on the northern side of the WAB. SU2 has not been observed offshore Morocco. As can be seen in Figure 12 (CAB01-123 and CAB01-125), its internal seismic attributes are relatively homogeneous and its underlying boundary with SU1 is well marked by a high amplitude (red-to-blue couple) reflector. The spatial distribution of SU2 is difficult to assess across the WAB. It can easily be traced in places where mud volcanic activity does not disturb the acoustic signal (Fig. 5, 7) but offshore Morocco, its distribution is more confusing. This statement is of importance for the discussion regarding the mud volcano root at depth.

**Interpretation** - This seismic unit has not been reached by drilling in the Western Alboran Basin. Its seismic facies could mark the presence of carbonate beds or even coarse-grained siliciclastic deposits. It is the first sedimentary record of the basin overlying the “pre-rift” sequence SU1, and could thus be linked to the Lower Miocene deep marine deposits identified in the Alboran-A1 borehole, defined as an olistostromic unit (Jurado and Comas, 1992; Comas *et al.*, 1999) made up of shales, slightly calcareous siltstone and sandstones. Onshore, the oldest post-nappe deposits are composed of late Oligocene-Aquitainian and Burdigalian formations called Ciudad Granada-Fnideq and Viñuela-Sidi Abdeslam, respectively (Serrano *et al.*, 2007; Hlila *et al.*, 2008). These formations consist of proximal marine breccias and conglomerates passing to deep marine siliciclastics (marlstone, sandstone or pelagic shales), the Viñuela-Sidi Abdeslam formations being more distal. The contact between these two units becomes nearly conformable in the central parts of the depocenter (Serrano *et al.*, 2007; Hlila *et al.*, 2008) making their respective identification on seismic lines difficult (Martínez del Olmo and Comas, 2008). SU2 could represent such Early Miocene deposits in the deepest part of the basin and could consequently be attributed to the late Aquitainian-Burdigalian. However, this suggestion should be interpreted with caution, as the only microfossil partially marking the late Burdigalian (e.g. *Praeorbulina sicana*, occurrence from 16.38 to 14.53 Ma; Anthonissen and Ogg, 2012) retrieved in the bottom 87 m of the Andalucía-G1 well belongs to the upper seismic unit SU3.

### 5.1.3. SU3

**Description** – The seismic unit SU3 is bounded below by a moderate to high amplitude and continuous reflector R3 (Fig. 5, 11). SU3 is composed of moderate amplitude and low frequency discontinuous reflections packages. Its seismic facies is frequently marked by chaotic reflections with acoustic diffractions patterns, and also by the occurrence of low frequency and high amplitude segments (Fig. 7). Basal lap terminations are visible locally on the R3 reflector. SU3 lies unconformably over SU2 or SU1 units (Fig. 5, 7, 8, 11). SU3 is marked by local variations in thickness: offshore Spain, its thickness can reach up to 2,000 m (based on an internal seismic velocity of 2,500 m/s); offshore Morocco, SU3 is thinner and reaches only 500 ms TWT in the central part of the WAB. SU3 pinches out against SU1 or the basement (Fig. 10, 11).

**Interpretation** – SU3, which is tied to the Andalucia-G1 borehole, corresponds to the section located between 3,090 and 3,716 mbsf, which is mostly composed of greenish to reddish shales above a basal marine conglomerate (Fig. 4). The interval between 3,640 and 3,140 m.b.s.f. has a microfauna rich in reworked Cretaceous species and only rare Miocene species (Fig. 4). Along with the chaotic seismic facies including contoured preserved bedding (SU3 in Fig. 5), this configuration is in favor of gravity-flow deposits. In the El Jebha borehole, part of the lower shaly sandstone interval could belong to this unit (Fig. 4, 6). Logging data show the occurrence of undercompacted shales within the unit dated from the Langhian based on its foraminiferal content (Fig. 4; Soto *et al.*, 2010). At the base of the Andalucia-G1 well, the occurrence of *Praeorbulina sicana* characterizing the late Burdigalian-Early Langhian (occurrence from 16.38 to 14.53 Ma; Anthonissen and Ogg, 2012) suggests a possible older age of the lower part of the unit (industry well report). Shale and mud intrusions, causing mud volcanism in the WAB (Sautkin *et al.*, 2003; Somoza *et al.*, 2012; Gennari *et al.*, 2013), appear to be mostly rooted in this deep unit SU3 according to the seismic images (Fig. 9, 10, 12). This observation is in agreement with micro-paleontological identifications made in several mud volcanoes showing the occurrence of Early to Middle Miocene foraminifers in the shaly matrix of mud breccias (Sautkin *et al.*, 2003; Gennari *et al.*, 2013). The occurrence of mud at depth obstructs and deforms the acoustic signal making the deep roots of the mud pipes difficult to assess. It is thus reasonable to assume that the mud volcanoes of the WAB are at least rooted in the deep SU2 and SU3.

### 5.1.4. SU4

**Description** – SU4 unconformably lies on SU1 to SU3 units showing onlap geometries toward the edge of the basin (Fig. 5, 6, 7, 8). SU4 is characterized by two distinct seismic facies: one consists of variable amplitude, laterally continuous, parallel reflectors, whereas the second consists of

lower amplitude reflectors locally displaying transparent reflection. Chaotic reflections were also identified at the base of the SU4 mega sequence (Fig. 8). The internal unconformities enabled the identification of three sub-units from the bottom to the top SU4a to SU4c:

- Sub-unit SU4a is characterized by low to moderate amplitude, moderate frequency continuous sheeted reflectors (Fig. 5, 7). Locally, the seismic facies evolve to a low frequency reflection package presenting disrupted reflectors (East of CAB-102 seismic line; Fig. 7).

- Sub-unit SU4b is characterized by low to moderate amplitude, continuous sheeted reflectors (Fig. 5, 6, 7) displaying an erosive basal surface (Fig. 8). The amplitude and frequency of the reflection package increase from the northern to the southern side of the WAB (Fig. 5, 9, 10).

- Sub-unit SU4c presents a similar seismic facies signature to subunit SU4a composed of low to moderate amplitude, moderate frequency continuous sheeted reflectors (Fig. 5, 7). Its basal reflector is marked by the truncated reflectors of the overlying subunit SU4b, and by onlap terminations of SU4c (Fig. 5, 8, 9, 10).

The overall geometry of SU4 shows basinward thickening that is not affected by the NW-SE transpressional zone crossing the basin at its center (Fig. 10, 11). However, normal faults on the Moroccan upper slope (western side of CAB01-132 and 140, Fig. 10) appear to have controlled part of the sedimentation, as basinward thickening is observed in sub-unit SU4a. These normal faults could have been active during the deposition of SU3 and SU4 (Fig. 10) and reactivated later. They are rooted at the interface of SU1a and SU1b (Fig. 10, 11).

**Interpretation** – SU4, tied to the Andalucia-G1 and El Jebha boreholes, is mostly composed of sandstones, conglomerates, shaly sandstones and clayey layers dated from the Serravallian (Fig. 4, 5, 6). In the middle of the Serravallian section, ~240 m of volcanoclastic layers composed of sandstones and shales alternating with acidic volcanic layers could represent the highest amplitude reflectors visible in the SU4b sub-unit (Fig. 5, 7). The seismic facies of subunits SU4a and SU4c marks the deposition of prograding clastics along the margin (fan delta) and siliciclastic sheeted turbidites in the deepest part of the basin interbedded with hemipelagic deposits. Landward-stepping stacking patterns of sub-units SU4a to SU4c shows an overall net increase in the accommodation space during deposition of the SU4 mega-sequence. A significant change can be observed at the base of SU4c (Fig. 11). Although no significant channel features were observed in our seismic data, internal reflections suggest the presence of sheeted turbidites and compensating lobes geometries. Hence, Serravallian depositional facies architecture reflects episodic subsidence patterns, with basin-centered facies tracts (turbidites).

### 5.1.5. SU5

**Description** – unit SU5, unconformably overlying SU4 is composed of two sub-units, SU5a and SU5b, separated by a high amplitude unconformable reflector R5b on which baselap terminations were observed (Fig. 5). SU5 onlaps on SU4 and basement units (Fig. 5, 8). Internal reflections of subunits SU5a and SU5b are characterized by low to moderate amplitude, moderate frequency continuous sheeted reflectors (Fig. 5). The internal reflection pattern of SU5b resembles that of SU4 but with a higher frequency in its upper part (Fig. 7). The geometry of SU5 shows a basinward thickening where the acoustic imagery is disturbed by the central transpressional zone (Fig. 10, 11) but no major offset is observed.

**Interpretation** – SU5 is composed of similar materials to those of SU4. In the Andalucia-G1 and El Jebha boreholes, SU5 is composed of fine-grained to coarse-grained sandstones together with shaly sandstones, marls and shales dated to the Tortonian (Fig. 4). At that time, the basin underwent deep-water hemipelagic deposition of shales intercalated with turbiditic sheets. Seaward- to landward-stepping stacking patterns of SU5a and SU5b record the continued increase in accommodation space initiated during SU4 mega-sequence deposition. The arcuate central Alboran topographic high is buried by the siliciclastic flux from the top of the SU4c (late Serravallian) as revealed by seismic interpretation and confirmed by the results of drilling at the ODP 976 site (Comas *et al.*, 1999).

### 5.1.6. SU6

**Description** – the SU6 unit presents mainly parallel to sub-parallel reflections (Fig. 5), characterized by moderate to low amplitude, low to moderate frequency reflectors above a conspicuous unconformity marked by a high-angle onlap on SU5 and the basement (Fig. 5, 8). This unit thickens toward the center of the basin to reach 1.3 s TWTT (Fig. 9, 10, 11). In the eastern part of the WAB, SU6 is made up of the superposition of three successive packages of low to high amplitude continuous reflectors (Fig. 9), pinching out towards the edge of the basin (Fig. 11). SU6 is affected by minor normal faulting on the Moroccan upper slope (Fig. 10) but in Figures 9 and 10, it is quite clear that the transpressional fault zone, marked by the mud volcanism perturbations on the acoustic signal, was active at that period.

**Interpretation** – SU6 has been drilled both in Andalucia-G1 and El Jebha boreholes, showing that it comprises sandstone interlayered with marl and clay beds from the Upper Tortonian- Messinian (Fig. 4). These layers have been interpreted as thin turbiditic deposits interlayered within hemipelagic sediments (Jurado and Comas, 1992). SU6 corresponds to the Unit III described by Jurado and Comas (1992), and lasted from the Upper Tortonian to the lowermost Messinian (synthesis in Comas *et al.*, 1999). According to previous studies, the basal unconformity of this unit marks the compressive

inversion of the entire Alboran Sea due to the Africa-Europe convergence. The basin-wide unconformity R6 is linked to the well-known contractive reorganization of the basin, starting around 8 Ma (Comas *et al.*, 1999; Do Couto *et al.*, 2014b). Toward the edges of the basin, progressive onlap shifts onto the basement suggest the occurrence of a tectonic event preceding SU6 deposition. R6 unconformity is characterized by chaotic reflections interpreted as a basal mass transport event probably related to a major change in tectonic activity at this time.

#### 5.1.7. SU7

**Description** – The upper bounding surface of SU6 displays a large number of truncations and is locally covered by a relatively thin seismic unit with a small number of low to moderate amplitude chaotic reflectors (Fig. 7). At the base of the unit, high amplitude reflectors pinch out toward the Spanish margin. At the scale of the basin, this unit SU7 is thin, rarely exceeding 350 ms TWTT.

**Interpretation** –the Andalucia-G1 well drilled in SU7 comprises two sub-units with - from bottom to top - a volcanoclastic series made up of intercalated clays and basaltic layers under marine sandstones interbedded with finely laminated beds and shallow carbonate, with some gypsum and thin anhydrite intervals (Jurado and Comas, 1992). SU7 corresponds to Unit II described by Jurado and Comas (1992). The chaotic facies have been interpreted as mass transport deposits (Martínez del Olmo and Comas, 2008) linked to the sea level drop during the Messinian Salinity Crisis in the Mediterranean Sea.

#### 5.1.8. SU8

**Description** –Horizon R8 (Fig. 5) bounding SU8 has a complex erosional surface. This unit is composed of low amplitude and high frequency sub-parallel reflectors evolving upward to high amplitude prograding, mound shaped and sub-parallel reflectors (Fig. 5, 7, 8, 9). Within the unit, internal erosive surfaces separate the lower low amplitude reflection package from the higher amplitude upper one (Fig. 9).

**Interpretation** –SU8, identified as Unit I in Jurado and Comas (1992), consists of pelagic to hemipelagic marls and clays, interlayered with sandy turbidites (Alonso *et al.*, 1999) dated from the Pliocene and Quaternary. The basal erosional surface marks the imprints of the Messinian Salinity Crisis in the Alboran Sea (Estrada *et al.*, 2011). Where erosion related to the Messinian Salinity Crisis is high, the Pliocene-Quaternary SU8 overlies older Tortonian to Serravallian deposits (Fig. 5, 8). In the Alboran Sea, a large number of contourite systems were caused by currents that affected the Mediterranean during the Pliocene and Quaternary (Palomino *et al.*, 2011; Somoza *et al.*, 2012).

## 5.2. Isopach mapping

Based on our seismic interpretation, isochore maps were generated for each seismic unit and were depth-converted using mean interval velocities derived from the Andalusia-G1 and El Jebha industrial boreholes. The mean velocities used to calculate the different isopach maps are rounded values applied to outline the velocity trend observed in the wells.

The depth to basement map (Fig. 13A) was computed from the commercial 2D seismic dataset presented in Fig 2B, together with hundreds of academic seismic datasets, and represents the morphology of the metamorphic basement beneath the basin infill. The deepest depression reaches 8 s TWTT offshore Morocco and no more than 7 s offshore Spain. This is in agreement with previous estimates (Soto *et al.*, 1996; Mauffret *et al.*, 2007; Iribarren *et al.*, 2009; Soto *et al.*, 2010). All tectonic structures identified on seismic profiles show the effect of the inversion on the Alboran Sea basement. Numerous faults have been mapped throughout the Xauen Bank, showing reverse offset, or at least transpressional movement, considering the small vertical offset (Fig. 9) and the presence of several folded structures (Chalouan *et al.*, 1997; Ammar *et al.*, 2007). From the Alboran Ridge to the Xauen Bank, all faults and structures tend to parallel the Moroccan coast (Fig. 13A). A sinistral strike-slip component is likely to have occurred beneath the Xauen Bank to accommodate the northward African plate convergence, as suggested by Chalouan *et al.* (1997). The basin floor reflector R1 is disrupted by several faults with relatively low vertical displacement across the sedimentary pile (Fig. 10, 11). The alignment of these structures from south to north and their relatively steep pattern suggest the development of a wide NW-SE oriented transpressional fault zone. Given the associated mud volcanism, activity appears to be recent (Fig. 10, 11).

The isopach map of the pre-rift unit SU1 reveals that its thickest series are mostly concentrated along a NW-SE sedimentary package located on the western slope of the basement (Fig. 13B). On the Spanish side, two smaller packages reaching 2 s TWTT in thickness can be distinguished. The overall distribution of this unit is constrained on the Moroccan side of the WAB, where the compressive to transpressive deformation of the basin does not affect the thickness of the unit, which thus seems younger.

The main depocenter of the syn-rift seismic units of the Western Alboran Basin (SU2 and SU3), dated from the late Aquitanian-Burdigalian to the Langhian, is located along a roughly WSW-ENE trough parallel to the Spanish coastline (Fig. 13C). Its thickness can reach 2 s TWTT (Fig. 7, 13C) but on the southern side of the basin, never exceeds 700 ms TWTT. It should be noted that the seismic units SU2 and SU3 are grouped together because (1) they most probably mark the Early Miocene period (even if the SU2 unit has not been drilled) and (2) the spatial distribution of the SU2

unit is rather limited offshore Spain, and thus appears to mark a more local sub-unit. In the central part of the WAB, the thickness rarely reaches 1 s TWTT, and generally does not exceed 500 to 750 ms TWTT. The involvement of undercompacted shales in the mud volcanism, together with the strong tectonic imprints in the southern WAB, render precise observations of the complete distribution of these units impossible.

The Serravallian (SU4) isopach map revealed significant reorganization of the depocenter with an acceleration of subsidence: a thick depocenter mimics the Gibraltar orogenic arc (Fig. 13D). Even with a large area of poorly imaged reflections where uncertainties remain in the seismic correlation (due to perturbations of mud/shale volcanism) in front of the Strait of Gibraltar, the thickness of these turbiditic deposits is similar over the whole basin, with a maximum thickness of about 2 s TWTT. A southeastward shift in the location of the Lower Tortonian (SU5) depocenter is observed with more than 1 s TWTT of sediments in the central part of the basin and a decrease in thickness to less than 750 ms in its northern part (Fig. 13E). The Upper Tortonian unit (SU6) reveals similar trends to those of the Lower Tortonian unit (SU5), with a maximum thickness of 1 to 1.25 s TWTT in the central part of the basin. This northward shift of the depocenter is linked to the regional compressive deformation that started at that time: the thickest depocenter is located at the front of distal thrusts (Fig. 11, 13F) while the Xauen Bank is folded and delineates E-W oriented synclines (Fig. 13F). Offshore Spain, the Upper Tortonian is reduced to 750 ms TWTT. The Pliocene to Quaternary isopach map presents the main depocenter that is still active as the western Ceuta drift, made of contouritic deposits and exceeding 1.5 s TWTT (Fig. 13G).

## 6. Discussion of the seismic interpretation

### 6.1. Age and significance of the pre-rift sequence SU1

Over the years and with the improvement in seismic acquisition and treatment, SU1 has been interpreted in different ways, *e.g.* as belonging to the basement (Morley, 1993), as defining a Middle Miocene unit (Chalouan *et al.*, 1997) or as representing the late Oligocene-Early Miocene older post-nappe sediments (Mauffret *et al.*, 2007). These interpretations were based on the strong chaotic facies imaged on old seismic profiles. The recent 2D seismic dataset presented here makes it possible to refine its significance and age.

The SU1 sequence lies on the acoustic basement over a high-amplitude continuous to semi-continuous reflector R1 (Fig. 8, 10, 11, 12). In the northern Moroccan margin, its seismic facies, composed of moderate to high amplitude chaotic reflections, contains sigmoidal internal reflections. The flattening of the CAB01-116 seismic line at the top of the Serravallian unit (SU4) displays the paleo-topography of SU1 during the deposition of Langhian to Serravallian deposits (Fig. 14). The

orientation and shape of these sigmoidal reflections within the SU1b unit reflect a strong chaotic internal deformation. Offshore Spain, the Early Miocene olistostromic unit contains a similar seismic facies and structural characteristics (Martínez del Olmo and Comas, 2008). In the central Moroccan margin, the internal chaotic facies tends to disappear and SU1 is affected by landward normal faulting that affects the series up to the Serravallian (CAB01-132; Fig. 14). Langhian (SU3) and Serravallian (SU4) deposits onlap the SU1 unit, suggesting that the internal structuration of SU1 took place before the infill of the WAB (Fig. 14). Onlapping geometries can be observed all along the Moroccan margin, and the angular unconformity increases southward (Fig. 11, 14).

The high amplitude, continuous reflectors developed in the SU1b sub-unit (CAB01-140; Fig. 11, 14) do not support the hypothesis of an olistostromic unit made of an extensive shaly matrix including heterometric and polymictic blocks. However, its seismic facies rather suggest the presence of carbonated beds or siliciclastics deposits like condensed turbiditic layers (Fig. 11). Unlike the Early Miocene sequence offshore Spain (Martínez del Olmo and Comas, 2008), the seismic reflections of the SU1 unit are higher in amplitude, and the isopach map shows that the thickest part of the unit does not fill the main depression but lies on the lower Moroccan slope (Fig. 13B). Based on a mean interval velocity of between 2,500 m/s or 3,000 m/s for the SU1 (depending on its lithology), the average thickness of SU1 can be estimated at 2 to 3 km (Fig. 14). The thickness of the late Oligocene-Early Miocene post-nappe deposits (Fnideq and Sidi Abdeslam formations: Serrano *et al.*, 2007) recognized onshore never exceed 500 m (Zaghloul *et al.*, 2003; Hlila *et al.*, 2008), which does not seem to be sufficient to represent the SU1 sequence.

The SU1 unit is intercalated between the acoustic metamorphic basement and the Miocene series, resting as a tilted unit on the Moroccan margin. Its seismic facies, its thickness, the lack of extensional tectonics, do not support an olistostromic origin of SU1 in the late Oligocene-Early Miocene. We thus propose that the SU1 sequence represents a pre-rift unit on which the late Oligocene-Early Miocene formations transgress and, according to the geology of the Rif, two formations made of sediments are intercalated between the metamorphic basement and the Miocene series, 1) the Ghomaride unit (Feinberg *et al.* 1990; Durand-Delga *et al.*, 1993; Zaghloul *et al.*, 2003; Hlila *et al.*, 2008) and 2) the backthrust Maghrebien flysch klippe (see synthesis in Chalouan *et al.*, 2008). As the latter is unlikely to reach the extension and thickness of SU1 (given the limited shape of the Maghrebien flysch klippe onshore), we opt for the Ghomaride complex. The Ghomaride unit is the topmost nappe composing the Alboran domain and mainly consist of slightly metamorphic Paleozoic successions (Chalouan, 1986) covered by Mesozoic-Cenozoic sedimentary successions. Mesozoic series are made of Triassic reddish sandstones and conglomerates, Liassic limestones and reddish silts and late Eocene Nummulitic limestones and calcareous conglomerates (Chalouan and Michard, 1990; Maaté *et al.*, 2000; El Kadiri *et al.*, 2006; Martín-Martín *et al.*, 2006). The Ghomaride unit is separated from the Alpujarride-Sebtide by an extensional detachment (Chalouan and Michard, 1990). Its

thickness varies and can reach 3 to 5 km (Chalouan and Michard 1990), which is the mean estimated thickness of SU1 offshore (Fig. 13B). The internal chaotic facies observed on the northern Moroccan margin (CAB01-116 seismic line; Fig. 14), suggest that part of the deformation accompanying the Ghomaride emplacement results from gravity-driven tectonics. This observation is in agreement with the Ghomaride origin of clastics of the Ciudad Granada-Fnideq and the Viñuela-Sidi Abdeslam formations (Durand-Delga *et al.*, 1993; Serrano *et al.*, 2007; Hlila *et al.*, 2008).

## 6.2. Tectono-stratigraphic history of the Western Alboran Basin

### 6.2.1. Mode of extension

Contrary to the Spanish margin where extension occurred during the Early to Middle Miocene (Martínez del Olmo and Comas, 2008; Soto *et al.*, 2010), the lack of a coeval extensional structure is surprising along the Moroccan margin. It is even more surprising that the seismic profiles interpreted on the Moroccan margin are SW-NE oriented, *i.e.* more or less in the same direction as the well-documented extensional regime that lasted from the Middle to the Upper Miocene (Jabaloy *et al.*, 1992; Martinez-Martinez and Azañon, 1997; Martínez-Martínez *et al.*, 2002a, 2002b). Indeed, with respect to the pre-rift unit SU1 and the metamorphic basement, the stratigraphic relation of the Miocene basin fill does not display much normal faulting. The Miocene basin fill (from SU2 to SU7) onlaps its margins (Fig. 14, 15) and the contacts between sediments and pre-basin units are mostly stratigraphic. The geometry is essentially that of a sag basin, at least after the Serravallian where the stratal terminations show onlap geometries on both sides of the basin, even looking parallel to the direction of extension, with relatively homogeneous subsidence. This observation contradicts previous tectonic models of the WAB formation that invoked steep extensional faulting, or a strike-slip tectonic context (Bourgois *et al.*, 1992; Mauffret *et al.*, 2007). Consequently, the mode of extension at the origin of the Early Miocene initial subsidence, and post-thinning subsidence must be sought in other processes.

In the Early Miocene, when sedimentary deposition started in the Western Alboran Basin, the Alpujarride-Sebtide metamorphic basement of the Alboran domain experienced a progressive exhumation marked by a fast cooling path from ~400 °C at 18-20 Ma (Monié *et al.*, 1994, Platt *et al.*, 2003), to ~100 °C at 17-16 Ma (Johnson *et al.*, 1997; Platt *et al.*, 2005; Vázquez *et al.*, 2011). The coeval crustal extension resulted in the exhumation of high-pressure rocks and the thinning of the crust accompanied by low-angle brittle normal faults (Crespo-Blanc, 1995). The contact between the Alpujarride-Sebtide and the Ghomaride nappes has been documented as an extensional shear-zone (or detachment) (García-Dueñas *et al.*, 1992; Lonergan and Platt, 1995; Crespo-Blanc, 1995; Platt *et al.*, 2005; Augier *et al.*, 2005a), which, during the late Oligocene-Early Miocene, acted through a N-S to NNE-SSW stretching direction (22 to 18 Ma) (Monié *et al.*, 1994; Crespo-Blanc *et al.*, 1994; Crespo-

Blanc, 1995; Platt and Whitehouse, 1999; Hurford *et al.*, 1999; Platt *et al.*, 2005). The continuous basal contact of SU1 observed on the Moroccan margin (i.e. the top of acoustic basement) could represent such a detachment which today is tilted and sealed by the late Aquitanian-Burdigalian to Langhian SU2 and SU3 (Fig. 10, 11). Offshore Spain, the contact separating the Miocene series and the metamorphic Alpujarride-Sebtide basement has been interpreted as a detachment ramp (Martínez del Olmo and Comas, 2008; Soto *et al.*, 2010). Moreover, a long history of extensional growth faults that accompanied the basin tilting and subsidence in the Early-Middle Miocene has been documented (Soto *et al.*, 2010; Giraldo and Hermoza, 2013). Offshore Morocco, the base of the Ghomaride unit (SU1) has also been said to act as a detachment fault during the late Oligocene-Early Miocene and the exhumation of the Alpujarride-Sebtide complex (Chalouan *et al.*, 1995), but the following extensional tectonics remain unclear. In this area, in contrast to the Spanish margin, extensional structures such as normal faults strike mostly parallel to the coastline (Fig. 13) and do not display a major offset (Fig. 10, 11) or gravity-driven tectonics. In the western part of the WAB, the contact separating the Burdigalian-Langhian (SU3) from the Ghomaride unit (SU1) does not display extensional structures resembling those visible offshore Spain (rollovers and listric faults) (Martínez del Olmo and Comas, 2008; Soto *et al.*, 2010). However, south of the Xauen Bank, Chalouan *et al.* (1997) interpreted divergent onlap geometry over the acoustic basement highlighted by the Ghomaride unit (SU1; Fig. 8), and suggested a similar extensional detachment process to that described on the Spanish margin (Soto *et al.*, 2010).

Placed in a wider context, these observations of seismic profiles illustrate probably strong control of extensional detachments in the early architecture of the Western Alboran Basin. It appears to be difficult, if not impossible, to reconstruct the dimension, and the evolution of such extensional detachment below the basin over time because of the complex following tectonic history. However, all observations and previous studies conducted in the Betic-Rif ranges show that the kinematics of the extension at that period is marked by a N-S regional penetrative extensional event (Crespo-Blanc *et al.*, 1994; Crespo-Blanc, 1995; Platt *et al.*, 2005). In that case, the lowermost SU2 and SU3 seismic units made up of shales would have been deposited as syn-kinematic sediments. The present-day geometries of the SU2 and SU3 seismic units show that most of the Early Miocene sediments are concentrated in a WSW-ENE trough more or less parallel to the Spanish coastline (Fig. 13C). Nevertheless, it has been shown that these sediments are largely involved in the extensional deformation on the Spanish margin and associated shale tectonism (Soto *et al.*, 2010) and it would be hazardous to conclude from its present-day distribution in the basin.

### 6.2.2. Tectonic and stratigraphic scenario

The undercompaction of shales in the Burdigalian-Langhian series (Jurado and Comas, 1992;

Soto *et al.*, 2010), the lack of late Oligocene-Aquitania sediments (Martínez del Olmo and Comas, 2008) or the P-T-t paths of the basement units (synthesis in Platt *et al.*, 2013) are different arguments used by authors to suggest rapid subsidence at basin initiation in the Western Alboran Basin. Such a subsidence has been tentatively explained by strike-slip tectonics and associated pull-apart mechanisms (Bourgeois *et al.*, 1992), by thermal cooling of the Alboran Sea basement forming a sag basin (Morley, 1992, 1993) or by a half-graben basin (Mauffret *et al.*, 2007). Our detailed seismic interpretation in a more regional context compared with field data, leads us to propose an alternative scenario.

The newly identified pre-rift sequence SU1, resting as a tilted unit upon which the Miocene series onlap, and interpreted as the Ghomaride unit, leads us to interpret the primary subsidence pulse of the Western Alboran Basin as the result of an extensional detachment, probably partly rooted in the Ghomaride-Sebtide interface (Fig. 15). Such a tectonic context has been documented onshore in the Early to Middle Miocene (Suades and Crespo-Blanc, 2013) and explains the rapid subsidence in the basin together with the tilting of the SU1 unit visible on the seismic lines (Fig. 15). The onlap geometry of Early Miocene deposits on the Ghomaride (Fig. 15) or Alpujarride-Sebtide basement (Martínez del Olmo and Comas, 2008) at the edge of the WAB suggests that the primary subsidence phase probably occurred in a subaerial environment, creating the accommodation space required for marine sedimentation. In the Betic and Rif belts, petrographic and sedimentological studies showed that the main clastic source of the late Aquitania-Early Miocene deposits (our seismic units SU2 and SU3) was erosion of the Malaguide-Ghomaride units (Durand-Delga *et al.*, 1993; Zaghloul *et al.*, 2003; Serrano *et al.*, 2007; Hlila *et al.*, 2008). Figure 15 explains how most of the Ghomaride unit could have been eroded on the Moroccan side (“hanging wall”), and could have been preserved in the deep basin due to the tilting of the margin along a low angle detachment leading to the rapid exhumation of the Alpujarride-Sebtide units (Fig. 18; cross sections a and b).

Paleontological studies of mud volcanoes revealed the presence of extruded pre-Langhian foraminifers (Sautkin *et al.*, 2003; Gennari *et al.*, 2013) suggesting that the main mud source is rooted in the late Aquitania-Burdigalian olistostromic unit in the entire WAB (our seismic units SU2 and possibly the base of SU3). This olistostromic unit, which is well developed in the northern branch of the WAB (Malaga basin; Comas *et al.*, 1992), was correlated with seismic unit SU2 (Fig. 5) mainly located offshore Spain. Even though seismic unit SU2 has not been formally identified offshore Morocco, seismic unit SU3 drilled in the Andalusia-G1 borehole, also incorporates pre-Langhian foraminifers and could also be a source of mud.

In the Betic and Rif hinterlands, the Langhian is marked by the sedimentation of an olistostromic formation separated from the Early Miocene by a sedimentary hiatus (Zaghloul *et al.*,

2010; Suades and Crespo-Blanc, 2013). In the Alboran Sea, our seismic interpretation shows that the Late Burdigalian-Langhian unit (SU3) is also separated from the late Aquitanian-Burdigalian unit (SU2) by an unconformity (Fig. 5, 7). Offshore Morocco, this basal sequence is deposited at the foot of the tilted and pre-structured Ghomaride unit (Fig. 10, 11, 13C, 15 cross-section b) but the distinction between the SU2 and SU3 is not clear.

From the Serravallian, the Alboran Sea was filled by a thick clastic and volcanoclastic sequence (SU4) (Fig. 10, 11, 15 cross section c) during a global regression cycle (Hardenbol *et al.*, 1998). That period marks the onset of the most significant subsidence phase of the basin interpreted as sag behavior. In the Betic and Rif hinterlands, the Serravallian is marked by hiatus and subaerial erosion of the region surrounding the WAB (Morel, 1987; Cunningham *et al.*, 1997; López-Garrido and Sanz de Galdeano, 1999) when the southeastern Betics basins were subject to marine sedimentation (Soria, 1993). Internal reflector geometries and unconformities observed in the seismic data (Fig. 5, 6, 10, 11) show an irregular subsidence rate during the deposition of SU4, thus arguing against a simple thermal contraction model following exhumation of the Alpujarride/Sebtide complex. The Serravallian depocenter appears to be homogeneous and has a curved shape, locally reaching 2 s TWTT (Fig. 13). This period of active subsidence is correlated with the uplift of the Betic and Rif hinterlands during the forelandward formation of fold-and-thrust belts (see synthesis in Crespo-Blanc and Frizon de Lamotte, 2006; Chalouan *et al.*, 2008). The unconformity marking the top of sub-unit SU4b in the upper Serravallian is coeval with a major volcanic period recorded in the entire basin (Duggen *et al.* 2005, 2008). The angular unconformity could thus be explained by the growth and thermal uplift of the Trans-Alboran magmatic arc. The Lower Tortonian is marked by continuous turbiditic sedimentation that filled the Alboran Sea basin with a slight deviation of the depocenter toward the south of the WAB (Fig. 13E). Offshore Morocco, SU5 does not display large-scale extensional features while syn-sedimentary faulting associated with rollover structure has been documented in the Spanish margin (Soto *et al.*, 2010). According to these authors, this period also corresponds to the latest extensional deformation due to gravity sliding. This period ends at the late Tortonian when the entire Alboran area started to be inverted after the cessation of E-W extension in the Alboran realm under the African plate convergence.

The late Tortonian tectonic inversion affected the southernmost border of the WAB where the Xauen Bank began to develop its actual transpressive structure made up of a succession of antiforms/synforms over a sinistral strike-slip set of faults (Fig. 13; Chalouan *et al.*, 1997). In response to the tectonic inversion, the main depocenter (SU6) developed in front of the Xauen Bank. In the deepest part of the WAB, the irregularity of the basement interface as well as the geometry of faulted folds argue in favor of a transpressive structure cross-cutting the basin along a roughly NW-SE trend (Fig. 13A). The apparent discontinuity of these structures suggests that a set of en-echelon faults affects the basin. Taking the NW to N verging convergence of the African plate into account

(Serpelloni *et al.*, 2007), these en-echelon faults could have had a dextral strike-slip component.

The progressive compressive tectonics, in addition to glacio-eustatic variations, led to successively closure of the marine corridors connecting the Alboran Sea to the Atlantic and, to a more regional extent, the entire Mediterranean Sea (Krijgsman *et al.*, 1999 ; Garcés *et al.*, 2001; Martín *et al.*, 2001; Warny *et al.*, 2003) ending with the Messinian Salinity Crisis (MSC). In the Alboran Sea basin, deposition of evaporites is postulated because of the occurrence of interlayered gypsum and anhydrite beds in Andalusia-G1 borehole (Fig. 4). MSC related deposits in the Alboran Sea are relatively thin across the WAB and reworked within mass-transport deposits (Martínez del Olmo and Comas, 2008; Martínez del Olmo, 2011). The return of marine conditions is marked by the Pliocene and Quaternary sequence (SU8) dominated by contourites, turbidite fans and sedimentary instabilities formed by the interplay between the Mediterranean water masses, glacio-eustatic changes and the rapid morphological changes due to active tectonic inversion (Hernández-Molina *et al.*, 2011).

To sum up, the WAB experienced three stages of subsidence comprising (1) initial rapid subsidence induced by an extensional detachment, (2) a large subsidence pulse in the Serravallian and Tortonian up to (3) the tectonic inversion of the entire domain and the resulting centripetal subsidence.

## 7. Geodynamic implications

### 7.1. Paleogeographic reconstructions

In the following, we present paleogeographic reconstructions (Fig. 16) from the late Oligocene to the present through which the initiation, development and migration of the Western Alboran Basin will be discussed. Paleogeographic maps were built relative to Iberia, going backward in time, but which we present from the oldest to the most recent. In parallel, four synthetic cross sections were drawn across the whole Betic-Rif orogenic system to follow its evolution (Fig. 17). The reconstructions are based on a simple scenario that involves a three-step evolution of the back-arc basin since the Oligocene (Jolivet *et al.*, 2003, 2006, 2008). The first period (before 20 Ma) witnessed the early development of the back-arc basin associated with N-S extension, the activity of the detachment localized between the Malaguides-Ghomarides and the Alpujarride-Sebtides, and the first development of sedimentary basins in the internal zones of the Betics. The second period saw a dramatic change in the direction of extension from N-S to E-W and the rapid westward motion of the Alboran domain until the renewal of N-S compression some 7 Ma ago. The map of the distribution of marine and land areas was drawn after Dercourt *et al.* (1993), Meulenkamp and Sissingh (2003), and Gibert *et al.* (2013).

### 7.1.1 Oligocene

In the Oligocene (30-25 Ma), the N-dipping subducted slab had a ~NNE-SSW oriented front that progressively retreated southward toward the North African margin. The main consequences were the first back-arc extension in the Alboran domain, intracontinental shortening in the Mesorif unit (Michard *et al.*, 2002) and subsidiary shortening along the Atlas system previously build up in the Eocene (Fig. 16; Frizon de Lamotte *et al.*, 2000, 2008). The latest Oligocene is marked by the intracrustal emplacement of peridotite slices within Alpujarride units (Fig. 17A; Hidas *et al.*, 2013; Precigout *et al.*, 2013).

The internal Alboran domain progressively emerges, as the Malaguide-Ghomaride nappe becomes the source of the External Betic foredeep sediments (Vera, 2000). A first magmatic occurrence, characterized by tholeiitic dyke intrusions (Turner *et al.*, 1999; Duggen *et al.*, 2004), marks the extensional deformation that affected the upper Malaguide/Ghomaride nappe (Zaghloul *et al.*, 2003; Serrano *et al.*, 2007; Hlila *et al.*, 2008). This extensional deformation resulted in the formation of small-scale basins where sedimentation is mostly terrigenous (Fig. 17A). In the late Oligocene, top-to-the N detachment tectonics led to the progressive unroofing of the Alpujarride/Sebtide basement currently forming the topographic high of the Alboran Sea (Fig. 1, 2A). Given the space available between the African and Iberian plates, as well as the extensional kinematics onshore, we infer that a SW-dipping detachment fault controlled the deposition of sediments and the coeval unroofing of the Alpujarride/Sebtide complex.

### 7.1.2. Aquitanian-Burdigalian

The southward retreat of the N-dipping subducted slab reached the African plate. This period saw the start of nappe emplacement in the frontal zones of the Betics and the Rif (Fig. 16; Lonergan and White, 1997; Platt *et al.*, 2003a). The Alpujarride/Sebtide complex shows syn-exhumation deformation associated with N-S to NE-SW trending stretching lineations (Crespo Blanc *et al.*, 1994, Crespo Blanc, 1995; Balanyá *et al.*, 1997; Platzman and Platt, 2004; Rossetti *et al.*, 2005; Negro *et al.*, 2008). A late Aquitanian thermal event affected the whole Alboran domain (Comas *et al.*, 1999; Soto and Platt, 1999) producing anatexic rocks and resetting most chronometers in the metamorphic rocks of the Alpujarrides (Fig. 16). This event has been correlated with an influx of hot asthenosphere material (Fig. 17; Negro *et al.*, 2006; Jolivet *et al.*, 2006).

Backstripping reconstructions have shown that the subsidence and first sediment loading in the Alboran Sea basin and in the southern Betics began in the late Oligocene-Early Miocene (i.e. 25-20 Ma; Docherty and Banda, 1995; Hanne *et al.*, 2003). The Burdigalian then underwent a rotation of the direction of extension from N-S to E-W (Fig. 16; Jolivet *et al.*, 2008). This particular change is interpreted as resulting from a westward slab tearing off from the North African slab. Contemporaneously with this dramatic change in extensional direction, the Western Alboran Basin

received its first sedimentary sequence unconformably covering the Malaguide/Ghomaride-Alpujarride/Sebtide extensional contact (our SU2 and part of SU3, Fig. 17B). To accommodate the exhumation of the Ronda and Beni Bousera mantle peridotites, the Malaguide/Ghomaride-Alpujarride/Sebtide contact visible in the WAB probably acted as a NNE-verging detachment ramp (Fig. 17).

### 7.1.3. Langhian-Serravallian

The Early Miocene-Middle Miocene transition marks a counterclockwise rotation of the direction of the African plate convergence (Fig. 16; Dewey *et al.*, 1989; Rosenbaum *et al.*, 2002a). Paleodynamic reconstructions correlate this rotation with a significant westward movement of the subduction zone (Lonergan and White, 1997; Jolivet *et al.*, 2003, 2006). This westward shift has been interpreted as the result of the roll-back and steepening of a narrow remnant of slab (Duggen *et al.*, 2005) or as the lateral tearing of the Tethys lithosphere subducted beneath the Betics (Wortel and Spakman, 2000). The External Zones of the Betic and Rif areas are marked by the forelandward progression of the compressional deformation, oblique collision in the Rif (Chalouan *et al.*, 2006) as well as the development of both the Guadalquivir and Gharb basins (Fig. 16). The shortening affecting the Flysch domain progressively diminished and local extension occurred (Crespo-Blanc and Frizon de Lamotte, 2006). At that time, the Gulf of Cadiz Imbricate Wedge developed in front of the migrating arcuate orogen (Maldonado *et al.*, 1999; Medialdea *et al.*, 2004). The Betic Internal Zones are marked by E–W extension with top-to-the W shearing of the lowermost Nevado-Filabride complex (Fig. 16; Jabaloy *et al.*, 1993; Johnson *et al.*, 1997; Augier *et al.*, 2005b;). The late Serravallian extensional tectonics caused basin subsidence in the southeastern Betics (Rodríguez-Fernández *et al.*, 2011) and then the early formation of sedimentary basins between the exhumed metamorphic domes (Fig. 17C; Ott d'Estevou and Montenat, 1990; Augier *et al.*, 2013; Do Couto *et al.*, 2014b).

In the Langhian, sedimentation of the in the peripheral basins is characterized by olistostromic formations made up of external zones with blocks embedded in a shaly matrix (Serrano *et al.*, 2007; Hlila *et al.*, 2008; Suades and Crespo-Blanc, 2013). In the Western Alboran Basin (SU3 unit) the Langhian is marked by the alternation of greenish to reddish clays with intercalated silts with local overpressure levels (Comas *et al.*, 1999). The transition to the Serravallian is well marked in the basin by an unconformity below a thick Serravallian siliciclastic sequence characterized by turbiditic deposits. Offshore the Spanish margin, Serravallian deposits unconformably cover the oldest extensional system coeval with the formation of the Alboran basin (Martínez del Olmo and Comas, 2008). This period saw the beginning of gravity-driven tectonics (Soto *et al.*, 2010). Offshore Morocco, the architecture of this sequence points to a sudden acceleration in subsidence in the WAB and sag-type behavior. This observation can be correlated with the still attached subducted slab underneath the North African margin and beneath the Betics.

#### 7.1.4. Tortonian

The Tortonian is a turning point in the evolution of the Betic-Rif orogen. The westward escape of the Alboran domain nearly stopped as it has been observed in the Gulf of Cadiz and in the Flysch domain (Medialdea *et al.*, 2004; Crespo-Blanc and Frizon de Lamotte, 2006). In the eastern Rif, the final oblique emplacement of the Alboran domain over the African plate is also marked by the top-to-the SW exhumation of the Temsamane units (Fig. 16; Negro *et al.*, 2006; 2008; Booth-Rea *et al.*, 2012).

The Tortonian deposits observed in the Betics seal the latest top-to-the WSW extensional shear zone (Crespo-Blanc *et al.*, 1994; Augier *et al.*, 2013). In the southeastern Betic Cordillera, the Early Tortonian is characterized by the continuation of extensional tectonics and basin subsidence (Ott d'Estevou and Montenat, 1990; Augier *et al.*, 2013; Do Couto *et al.*, 2014b). Extension continued until ~9 to 8 Ma when an uplift of the basin basement is recorded and extensional basins became partly inverted under the NNW convergence of the African and Eurasian plates (Fig. 17D; Weijermars *et al.*, 1985; Vissers *et al.*, 1995; Augier *et al.*, 2013; Do Couto *et al.*, 2014b).

The Tortonian sedimentation in the WAB is marked by two thick siliciclastic sequences (SU5a and b) made of turbiditic layers interbedded in hemipelagic sediments (Comas *et al.*, 1999) and showing a centripetal thickening in the WAB. These two SU5a and SU5b sequences are separated by a striking unconformity marking the onset of the compressive strain affecting the entire Alboran area (Martínez-García *et al.*, 2011, 2013). This unconformity, which was also observed by Talukder *et al.* (2003) appears to mark the end of a major episode of mud volcanic activity in the northern WAB. In the Alboran Sea, regional compression was accommodated along several strike-slip faults including the left-lateral Xauen-Alboran Ridge and Carboneras faults associated with the right-lateral Yusuf Fault (Fig. 16; Chalouan *et al.*, 1997; Ballesteros *et al.*, 2008; Martínez-García *et al.*, 2011, 2013). A roughly NNW-SSE-oriented transpressional fault zone also affected the WAB (Fig. 13). In the Betic Cordillera, compression resulted in the progressive uplift of various intramontane basins (Iribarren *et al.*, 2009).

#### 7.1.5. Messinian to present

Geodynamic reconstructions of the Messinian and present-day stages are similar (Fig. 16). Since the late Tortonian, the Betic-Rif system has been subjected to N-S compression and the E-dipping slab remains active (Comas *et al.*, 1999; Gutscher *et al.*, 2002; Duarte *et al.*, 2013). During the Messinian, this N-S compression together with eustatic fluctuations, progressively closed the Messinian corridors that had previously enabled the Mediterranean Sea to be filled with water from the Atlantic ended with the Messinian Salinity Crisis (Hsü *et al.*, 1973; Jolivet *et al.*, 2006; CIESM, 2008; Do Couto *et al.*, 2014a). Deformation of the WAB continues today and is marked by the inversion of the Xauen-Alboran Ridge transpressive fault (Watts *et al.*, 1993; Comas *et al.*, 1999;

Martínez-García *et al.*, 2011, 2013). The long-term effects of this shortening strain tend to delineate a domain escaping toward the southwest (Nocquet, 2012 and references therein) while the African crust slides against the Alboran domain. Since the late Tortonian and the tectonic inversion, the Alboran basin has evolved as a flexural basin. The post-Messinian reflooding of the area is marked by a large amount of contourite systems induced by currents that affected the Mediterranean in the Plio-Quaternary (Alonso *et al.*, 1999; Palomino *et al.*, 2011; Somoza *et al.*, 2012).

## 7.2. Location of the Alboran domain in the Early Miocene

Kinematic models proposing a slab rollback evolution of the westernmost Mediterranean involve a trench displacement of about 200 to 800 km (Rosenbaum *et al.*, 2002a; Faccenna *et al.*, 2004; Spakman and Wortel, 2004; Jolivet *et al.*, 2008). The reconstructed location of the internal Alboran domain thus varies considerably. Furthermore, it has been interpreted either as part of the Iberian margin or as an isolated microcontinent within the western Tethyan realm (Michard *et al.*, 2006). The farthest location puts the internal Alboran domain at the emplacement of the present-day Valencia trough (Rosenbaum *et al.*, 2002a), while other models propose a less distant origin south of the present-day Balearic Islands (Lacombe and Jolivet, 2005; Jolivet *et al.*, 2006). This assumption was re-assessed by Chalouan *et al.* (2008) based on plate kinematic reconstructions proposed by Schettino and Turco (2006). This location fits the African craton source and the southward paleogeographic extension of the Flychs units to the Alboran domain (Thomas *et al.*, 2010; Guerrera *et al.*, 2012; Alcalá *et al.*, 2013), as well as the Iberian craton provenance of plutonic pebbles retrieved from the Oligocene-Miocene cover of the Malaguide-Ghomaride complex (Gigliuto *et al.*, 2004; Puglisi, 2008). We therefore adopt this configuration as the location of the Alboran domain during the Early Miocene (Fig. 16). From the Early Miocene onward, our paleogeographic reconstructions indicate a westward slab retreat of about 600 to 700 km at an average velocity of 5 to 6 cm/yr (Fig. 16). Such a displacement is in agreement with previous estimates (Royden, 1993; Lonergan and White, 1997). The main acceleration step is thought to have taken place between the Burdigalian and Serravallian as the slab progressively detached along the North African margin and then beneath the Betic Cordillera (Jolivet *et al.*, 2006). This rapid westward roll-back caused the Alboran domain to overthrust the Flysch domain toward the west, the External Betics toward the north and the External Rif toward the southwest. A decrease in roll-back velocity occurred in the late Miocene, coeval with the resumption of compression after ca. 8 Ma.

The present day configuration of the WAB has an arcuated shape that mimics the curvature of the Gibraltar Arc (Fig. 2A). It is the result of successive extensional and compressional tectonics and we assume that the basin acquired its present shape in the late Tortonian, when the seismic unit SU6 covered and sealed most of the previous deformation. Unless a complete 3D restoration of the WAB is

undertaken, it will be complicated to recover the previous shape of the basin. Nevertheless, given the geodynamic restoration of the southwestern Mediterranean area (Fig. 16), the significant change in lithology from the shale-rich Burdigalian-Langhian (SU2 and SU3) to the Serravallian siliciclastic seismic units (SU4), we assume that the basin underwent a vertical-axis rotation, most probably clockwise, from the end of the Burdigalian up to the Langhian period. This would correspond to the change in the extensional regime recorded in the underlying metamorphic basement, from N-S to ~E-W (Fig. 15, 17).

### 7.3. Causes of the subsidence and migration of the WAB

In comparison with other onshore basins on the Betic and Rif belts, the Western Alboran Basin is surprisingly thick and, apart from recent localized compressional structures, hardly deformed (Ballesteros *et al.*, 2008; Martínez-García *et al.*, 2011, 2013). A thick pile of sediments has accumulated from the Early Miocene to the present with a depocenter that has not moved significantly with respect to the outline of the basin. During the westward retreat of the slab, one could have expected instead a migrating depocenter and overall regional extensional deformation like in the northern Apennines, for instance (Jolivet *et al.*, 1998). However, each sedimentary sequence unconformably covers the lower one, leading to the expansion of the basin area (Fig. 13). In comparison, onshore extensional basins are much thinner and are affected by numerous normal faults and detachments (Crespo-Blanc *et al.*, 1994; Crespo-Blanc, 1995; Meijninger and Vissers, 2006; Augier *et al.*, 2013; Do Couto *et al.*, 2014b). Such a difference in the tectonic style suggests a distinct formation process. The WAB most probably migrated westward together with the slab but with no significant deformation, while the metamorphic zones underneath were progressively extracted thanks to a series of detachments. Extensional detachments usually do not produce deep thick basins, as they tend to smear the deposition of sediments while progressively offsetting depocenters. The post-Caledonian Devonian basins in Norway are examples of this behavior (Seranne and Séguret, 1987; Osmundsen and Andersen, 1994), as are the southern Betics basins (Crespo-Blanc *et al.*, 1994; Crespo-Blanc, 1995; Meijninger and Vissers, 2006; Augier *et al.*, 2013).

The WAB does not follow this classical behavior. One possible explanation for the seemingly stable basin in such an unstable environment with a fast migrating upper plate and a constrained environment is that the basin has always been situated above the hinge of the retreating slab, as is the case today (Fig. 3). According to this hypothesis, the cause of subsidence was the constant presence of a dense anomaly at depth below the WAB that would depress the surface of the upper plate lithosphere thereby creating a space for sediment deposition (Fig. 18). As the slab migrated westward, the depocenter migrated at the same rate, and the underlying metamorphic domain was exhumed and the crust progressively thinned (Fig. 18). Such mechanical behavior has been used to explain the

subsidence and deformation of the Transylvanian sag basin (Tiliță *et al.*, 2013) and the larger intra-Carpathians realm (Matenco *et al.*, 2007; Ismail-Zadeh *et al.*, 2012).

The situation of the Western Alboran Basin is both specific and original at the edge of an active subduction zone. Paleomagnetic rotations on either side of the Gibraltar arc have been interpreted as reflecting Subduction-Transform Edge Propagator (STEP) fault activity at the edges of the lateral slab (Govers and Wortel, 2005). Very few places on Earth are in the same configuration but the integrated geodynamic model of the Alboran Sea and surroundings could actually be used as a model for other sedimentary basins in comparable situations such as the Cretan Sea, the Banda Sea or in the Caribbean Sea.

#### **7.4. Geodynamic, tectonic and sedimentary implications**

After a major change in the Mediterranean subduction regime during the Oligocene (Réhault *et al.*, 1984; Faccenna *et al.*, 1997; Jolivet and Faccenna, 2000; Jolivet *et al.*, 2008), the Tethyan subduction retreated progressively southward. From ~30 to 20 Ma, the Tethyan slab retreated toward the North African margin (Fig. 16). The Alboran domain consequently underwent N-S extension that led to the formation of low-angle normal faults in the Alpujarride/Sebtide complex following N-S ductile stretching. At that time, the WAB and adjacent small-scale satellite basins were formed. According to the primary depositional lithology, the first resulting subsidence pulse was relatively slow, characterized by coarse-grained conglomerates and pebbly sandstones evolving to more distal shale and turbidites (Zaghloul *et al.*, 2003; Serrano *et al.*, 2007; Hlila *et al.*, 2008). The dispersal of these outcrops onland as well as their subsequent tectonic deformation make it difficult to construct a paleogeographic map showing the connections between basins over time. Nevertheless, the common subsidence and sedimentation histories of the southern Betics and Rif sub-basins suggest an interconnection of marine corridors and depocenters (Fig. 16).

In the Lower Burdigalian, at ~20 Ma, a sudden event resulted in a widespread thermal overprint and local crustal anatexis (Platt and Whitehouse, 1999). During this period, N-S extension was still active in the Alpujarride/Sebtide complex (Fig. 18), active deposition of marine sediments occurred in the WAB (SU2 unit and probably part of the lowermost SU3), while E-W extension was starting to affect the underlying Nevado-Filabride complex (Augier *et al.*, 2005b). This particular change can be interpreted as the transition from southward to westward slab retreat. Subsequently, the whole Alboran domain migrated, driven by westward roll-back, tearing and local detachments of the subducting plate (Lonergan and White, 1997; Duggen *et al.*, 2004, 2005, 2008; Spakman and Wortel, 2004). That period also corresponds to the first occurrence of bimodal calc-alkaline magmatism in the northern Algerian margin which has been interpreted as the first geochemical evidence of slab tearing (Fig. 18; Maury *et al.*, 2000; Coulon *et al.*, 2002). In comparison with the late Oligocene-Aquitainian

configuration, the sedimentary context of the WAB remained quite similar in the sense that above the first late Oligocene-Early Miocene formations, a slight and mostly coastal unconformity is dated to the Aquitanian-Burdigalian boundary. The lithology of the overlying Burdigalian sequence indicates minor deepening of the basin (Serrano *et al.*, 2007; Hlila *et al.*, 2008). Such unconformity, combined with the exhumation of the Alpujarride/Sebtide rocks and their embedded peridotites (Afiri *et al.*, 2011), can be explained by the concomitance of top-to-the N low-angle normal faulting in the back-arc region and frontal thrusting of the Alboran domain over Africa (Fig. 16, 17, 18).

E-W extension proceeded through the Langhian and Serravallian together with the westward spread of the calc-calkaline magmatism in the North African margin (Fig. 16, 18). The inception of the Trans-Alboran calc-alkaline magmatism, marking the position of the deep subducted Tethyan lithosphere beneath the Alboran basin (Duggen *et al.*, 2005, 2008) took place in the Serravallian. The Nevado-Filabride complex was exhumed thanks to top-to-the WSW extensional shear zones (García-Dueñas *et al.*, 1992; Jabaloy *et al.*, 1993; Martínez-Martínez *et al.*, 2002a) while the Alpujarride/Sebtide complex was affected by top-to-the-N brittle normal faulting (Crespo-Blanc *et al.*, 1994; Rossetti *et al.*, 2005), coeval with the gravity-driven deformation of the WAB offshore Spain (Soto *et al.*, 2010). Two E-W oriented metamorphic domes were then progressively exhumed from E to W revealing the progressive evolution from ductile to brittle deformation (Augier *et al.*, 2005b; 2013) and triggering sedimentary deposition in the basins involved (Meijninger and Vissers, 2006; Augier *et al.*, 2013; Do Couto *et al.*, 2014b). The cartographic contour of the W-verging extensional detachment shows a complex curved pattern in the southeastern Betics (Fig. 18). In the WAB, this period saw the deposition of the Langhian shales in the SU3 unit and the following thick siliciclastics SU4 units. It is noteworthy that the thickest deposition of sediments in the WAB took place just after the extensional tectonic change. According to the seismic profiles, no major extensional deformation took place during the westward movement of the WAB, in contrast to the tectonic style documented offshore Spain (Soto *et al.*, 2010).

The assumption of slab tearing during the westward slab roll-back causing E-W extension in the southeastern Betics was reinforced by Le Pourhiet *et al.* (2012), who showed that metamorphic domes elongated parallel to the stretching direction (a-type domes, Jolivet *et al.*, 2004) can form thanks to a strike-slip shearing component. From the Langhian to Serravallian, the WAB filling underwent a substantial dynamic change. It is worth noting that the thickest sequence identified in the WAB is made up of siliciclastic deposits dated to the Serravallian and exceeding 3 km in thickness in the deepest part of the basin (Fig. 13). Backstripping analysis of the northeastern Alboran Sea and southern Betics revealed three periods of subsidence that took place in the Langhian (~15.5-14.5 Ma), Serravallian (~13-10.7 Ma) and in the Pliocene–Pleistocene (Rodríguez-Fernández *et al.*, 1999). In this geodynamic context, we suggest that these two successive Middle Miocene subsidence pulses were driven by the two successive North African and southern Betics slab tearing events. In the

Tortonian, the WAB acquired its curved shape mimicking that of the Gibraltar arc, which was about to stop its westward overthrust (Crepó-Blanc and Frizon de Lamotte, 2006).

The westward slab retreat remained active until ~8 Ma and the compressive inversion of the entire area (Fig. 16; Chalouan *et al.*, 1997; Ballesteros *et al.*, 2008; Martínez-García *et al.*, 2011, 2013). Paleomagnetic rotations continued in the Betics after the late Miocene, evidence for continuing displacement around the Gibraltar arc, probably favored by the contractional reorganization and a still active slab pull underneath (Mattei *et al.*, 2006; Duarte *et al.*, 2013). Today, the hinge of the subducted slab is still located underneath the deepest part of the basin. One can assume that this situation has been unchanged since the late Tortonian as no major recent deformation has been observed. We therefore postulate that the late Tortonian to recent thick sedimentary accumulation is the result of the N-S contraction of the Alboran domain (Cloetingh *et al.*, 1992; García-Castellanos *et al.*, 2002) driven by slab-pull at depth.

## 8. Conclusions

Based on analyses of recent 2D seismic profiles, combined with older seismic data and compiled field data, the tectonic and stratigraphic history of the Western Alboran Basin is clarified here.

Our stratigraphic analysis showed that a thick, pre-rift sequence is preserved beneath the Miocene Western Alboran basin. Land to sea correlations lead us to interpret this pre-rift series as the topmost Malaguide/Ghomaride nappe composing the Alboran domain, currently resting on top of the metamorphic basement. This series contains basal and internal interfaces thought to have acted as detachment faults during the Early Miocene exhumation of the underlying Alpujarride/Sebtide complex as well as during sediment loading of the basin coeval with the uplift of the Betic and Rif hinterlands.

The WAB and surrounding satellite basins record a low late Oligocene-Early Miocene subsidence phase generated by N-S extension exhuming the Alpujarride/Sebtide complex through deep rooted top-to-the N extensional detachment. In the meantime, the Alboran domain started to overthrust the Betic-Rif external zones. At the end of the Burdigalian, the N-S to E-W rollback transition triggered a moderate subsidence step in the WAB and adjacent basins. As E-W extension proceeded westwards, slab tearing occurred beneath the Betics leading to the exhumation of two E-W elongated domes, thereby triggering the onset of subsidence in the southeastern Betics. This modification of the lithospheric configuration largely affected the WAB, which recorded the onset of a strong subsidence phase, marked by an up to 3 km thick Serravallian sequence. This notable subsidence lasted until the late Tortonian and the inversion of the entire Alboran domain that marks

the beginning of the flexural filling of the WAB.

After the syn-rift sequence following unroofing of the metamorphic rocks dated to the Burdigalian-Langhian, the basin is marked by a basinwide subsidence period (sag basin) concomitant with high sedimentary influx that eroded the continuously uplifted hinterlands. Paleogeographic and paleodynamic reconstructions of the southwestern Mediterranean Sea from the Oligocene to the present illustrate the creation, migration and subsidence history of the Western Alboran Basin in relation with large-scale lithospheric processes. The roughly perpendicular change in slab rollback changed the shape of the WAB. Our observations, together with the tectonic timing of adjacent areas, suggest that the Western Alboran Basin has always been located above the hinge of the retreating slab, and that the slab-pull force has driven its subsidence. It is noteworthy that, apart from the gravity-driven deformation on the Spanish margin, the WAB has only a small number of normal faults, even with respect to the SW-NE basin-scale seismic lines parallel to the main extensional phase of tectonic evolution. We thus assume that the WAB was located above the dipping slab during its entire evolution and migrated with the retreating slab from east to west. We propose that the main cause of the rapid subsidence leading to the deposition of ~10 km of sediments in the center of the basin was the constant load of the downgoing slab during its westward retreat. The late Tortonian was marked by the tectonic inversion of the entire southern part of the basin, associated with a northward migration of the depocenter. The subsequent deformation was mostly localized above the thickest Serravalian-Lower Tortonian depocenters. After intense erosion related to the Messinian Salinity Crisis and reflooding of the basin, the Pliocene and Quaternary is marked by the still ongoing compressive strain, trapping a large amount of sediments along contouritic and turbiditic currents.

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### Figure captions:

Figure 1: Structural maps of the southern margin of the western Mediterranean Sea representing the main tectonic units and the location of the Western Alboran Basin (WAB). GK: Greater Kabylide; LK: Lesser Kabylide. The inset map shows the location of the Apennines, Tellian, Rif and Betic fold and thrust belts in the western Mediterranean.

Figure 2: A. Geological map of the Alboran Sea area showing major tectonic features of the Betic and Rif mountain belts and the location of the deepest depocenter in yellow (from Iribaren *et al.*, 2009). ODP sites 976 to 979, DSDP site 121, and all industrial wells are also located offshore (And G1 = Andalucía-G1; Alb A1 = Alborán-A1; And A1 = Andalucía-A1; El Jebha and Nador 1). AR = Alboran ridge; AI = Alboran Island; EAB = Eastern Alboran Basin; SAB = South Alboran Basin; WAB = western Alboran Basin; XB = Xauen bank; YF = Yusuf fault. Modified from Comas *et al.* (1992, 1999) and Martínez-García *et al.* (2011, 2013).

B. Map showing the location of the industrial (dark grey) and academic (light grey) seismic lines interpreted in the Western Alboran Basin. Blue lines (in two-way travel time and migrated depth), orange lines (in two-way travel time) represent the more recent 2D seismic acquisition (courtesy of ONHYM and ICM-CSIC Barcelona). The red transects are presented in this paper. List of industrial surveys: ALB-81, AM-74, AM-78, AM-79, AS-77, BRPM-80, EAS-74, ESCI-91, IZD-82, MO-75, SHL-75, TSH-83, CAB-01. List of academic surveys: ALHO-81, CONT-2010, CONR-88, GC-83, GC-90, ODP-95, MAB-2012, MAR-2011, MARG-2006, POLY-72, RAY-72, SAGAS-2010, SARAS-2012, TTR-2002, TYRO-91, WAT-91.

Figure 3: Geodynamic and tectonic context.

A. Hypocenter of the earthquake beneath the Alboran Sea and surroundings for  $M > 3$  (from <http://www.ign.es/ign/layout/sismo.do>). Two cross-sections, I and II, oriented NW-SE and SW-NE, respectively, show the relative position of the Western Alboran Basin above the sinking slab marked by the seismicity. See also Gutscher *et al.* (2002).

B. Crustal-scale geological cross-sections of the Alboran domain showing the overall tectono-stratigraphic framework from the External zones to the Internal zones, above which the Alboran Sea basin developed. Modified from Sánchez-Gómez *et al.* (2002), Crespo-Blanc and Frizon de Lamotte (2006), and using the Moho depth of Thurner *et al.* (2014). The inset in the upper right corner is a schematic yet intelligible view of the location of the western Alboran Basin with respect to the subducted slab geometry.

Figure 4: Stratigraphic logs of Andalucía-G1 and El Jebha industrial wells drilled on the northern and southern sides of the western Alboran Basin, respectively. The ages of the sedimentary sequences are re-assessed based on their paleontological content (biomarkers are listed in the middle column). The seismic units in the right-hand columns are those defined by Chalouan *et al.* (1997) and Comas *et al.* (1999) compared to the seismic units described in this study.

Figure 5: Uninterpreted and interpreted seismic profiles offshore Spain showing the northeastern WAB architecture tied to the Andalucía-G1 well. A correlation is made between the depth migrated CAB01-102, 123, 104 and 125 seismic sections with the CAB01-121 (in two-way time depth) as published by Soto *et al.* (2010). Basalap, when the layout pattern is ambiguous, and onlap terminations are frequently identified along our seismic sequence boundaries. 8 seismic units (from SU1 to SU8) were identified in the basin. The seismo-stratigraphic framework and mapped reflectors discussed in the text are labelled and the colors are consistent in all the following figures. Location of the seismic section in Fig. 2B. P: Pliocene; M: Messinian; T: Tortonian; S: Serravallian; L: Langhian; V.E.: vertical exaggeration.

Figure 6: Uninterpreted and interpreted CAB01-150 seismic profiles offshore Morocco showing the southern WAB architecture tied to the El Jebha well. 7 seismic units, from SU1 to SU8, were in this part of the basin. Note that the seismo-facies defined as SU2 offshore Spain has not been identified. Location of the seismic section in Fig. 2B. P: Pliocene; M: Messinian; T: Tortonian; S-L: Serravallian- Langhian.

Figure 7: A. Depth migrated CAB01-102 seismic section offshore Spain, showing the northern WAB architecture and the main stratal terminations of the sedimentary infill (courtesy of ICM-CSIC Barcelona). B. Interpretation of the main seismic units (SU1 to SU8) identified in the basin. Location of the seismic section in Fig. 2B. V.E.: vertical exaggeration.

Figure 8: A. NNW-SSE regional seismic section offshore Morocco (CAB01-101), showing the western side of the WAB architecture and the main stratal terminations of the sedimentary infill (courtesy of ONHYM). B. Interpretation of the main seismic units (SU1 to SU8) identified in the basin. Location of the seismic section in Fig. 2B.

Figure 9: A. NNW-SSE seismic section offshore Morocco (CAB01-111), showing the central WAB architecture and the main stratal terminations of the sedimentary infill (courtesy of ONHYM). B. Interpretation of the main seismic units (SU1 to SU8) identified in the basin. Location of the seismic section in Fig. 2B.

Figure 10: A. Regional SW-NE seismic section offshore Morocco (CAB01-132) crossing the WAB

and showing the deep architecture of the basin and the main stratal terminations of the sedimentary infill (courtesy of ONHYM). B. Interpretation of the main seismic units (SU1 to SU8) identified in the basin. Location of the seismic section in Fig. 2B.

Figure 11: A. Regional SW-NE seismic section offshore Morocco (CAB01-140) crossing the WAB and showing the deep architecture of the basin and the main stratal terminations of the sedimentary infill (courtesy of ONHYM). B. Interpretation of the main seismic units (SU1 to SU8) identified in the basin. Location of the seismic section in Fig. 2B.

Figure 12: Zoom on the seismic attributes of seismic units 1, 2 and 3 and their respecting boundaries. Seismic profiles CAB01-125, CAB01-123 and CAB01-140 are displayed using the pseudo-relief attribute developed by Kingdom Software ® which enables better observation of the internal structure of each seismic unit revealed by the acoustic impedance jump. R1 to R4 refer to the reflectors defined in Figure 6.

Figure 13: A. Depth to basement map interpolated from the 2D seismic dataset (in second two-way travel time). This horizon is affected by many faults from the Alboran Ridge (AR) through the Xauen Bank (XB), up to the WAB floor. B to G. Isopach map of the seismic units identified from the Pre-rift sequence SU1 to the Upper Tortonian SU6 and their associated deformation.

Figure 14: Seismic facies of the SU1 unit on the western side of the WAB seen on dip seismic lines flattened at the top of Serravallian. To the north, the upper SU1b sequence exhibits internal imbricated thrusts that do not affect the Middle Miocene series onlapping the SU1. Toward the south, both SU1a and SU1b are progressively characterized by moderate to high amplitude, semi-continuous to continuous reflectors.

Figure 15: Onshore-offshore chronostratigraphic correlation from Spain to Morocco showing the main unconformities that affect the whole domain (based on Ott d'Estevou and Montenat, 1990; Sanz de Galdeano and Vera, 1992; Vera, 2000; Zaghloul *et al.*, 2003; El Kadiri *et al.*, 2005; Sissingh, 2008; Zaghloul *et al.*, 2010; Rodríguez-Fernández, 2011; Suades and Crespo-Blanc, 2013), together with synthetic cross-sections showing the evolution of the western Alboran basin from late Oligocene (a) to the late Tortonian and the shift from extensional to contractional reorganization (d).

Figure 16: Paleogeographic maps of the southwestern Mediterranean region from the Early Oligocene to late Messinian displaying the main tectonic units and processes in the study area. The main geological structures, mostly compressive, are shown along with the location and successive deformation of the Flysch units, the volcanic events and the formation and development of the Western Alboran Basin. AR = Alboran ridge; YF = Yusuf fault.

Figure 17: Synthetic cross-sections of the Alboran domain showing the main tectonic units and exhumation processes over time. The cross-sections cross main structures perpendicularly from the south to the north including the north African subduction zone in the late Oligocene (A) or the Gibraltar arc represented by the Rif and Eastern Betics belts (B, C and D). In cross-section C, the top-to-the SW sense of shear of the extensional detachment between the Nevado-Filabrides and the Alpujarrides complexes is highlighted by two arrows in perspective.

Figure 18: Schematic three dimensional view and corresponding cross-sections of the westernmost Mediterranean region showing slab tearing and slab retreat following the slowing down of the

African plate due to collision with Eurasia. The WAB is in yellow.

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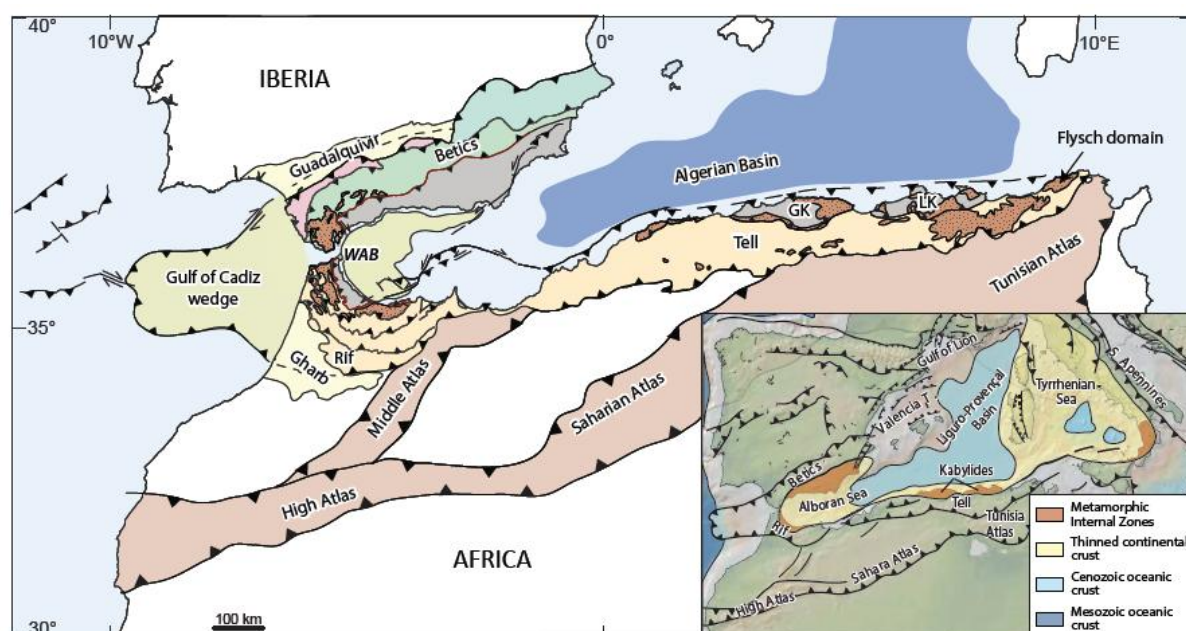


Figure 1



Figure 2

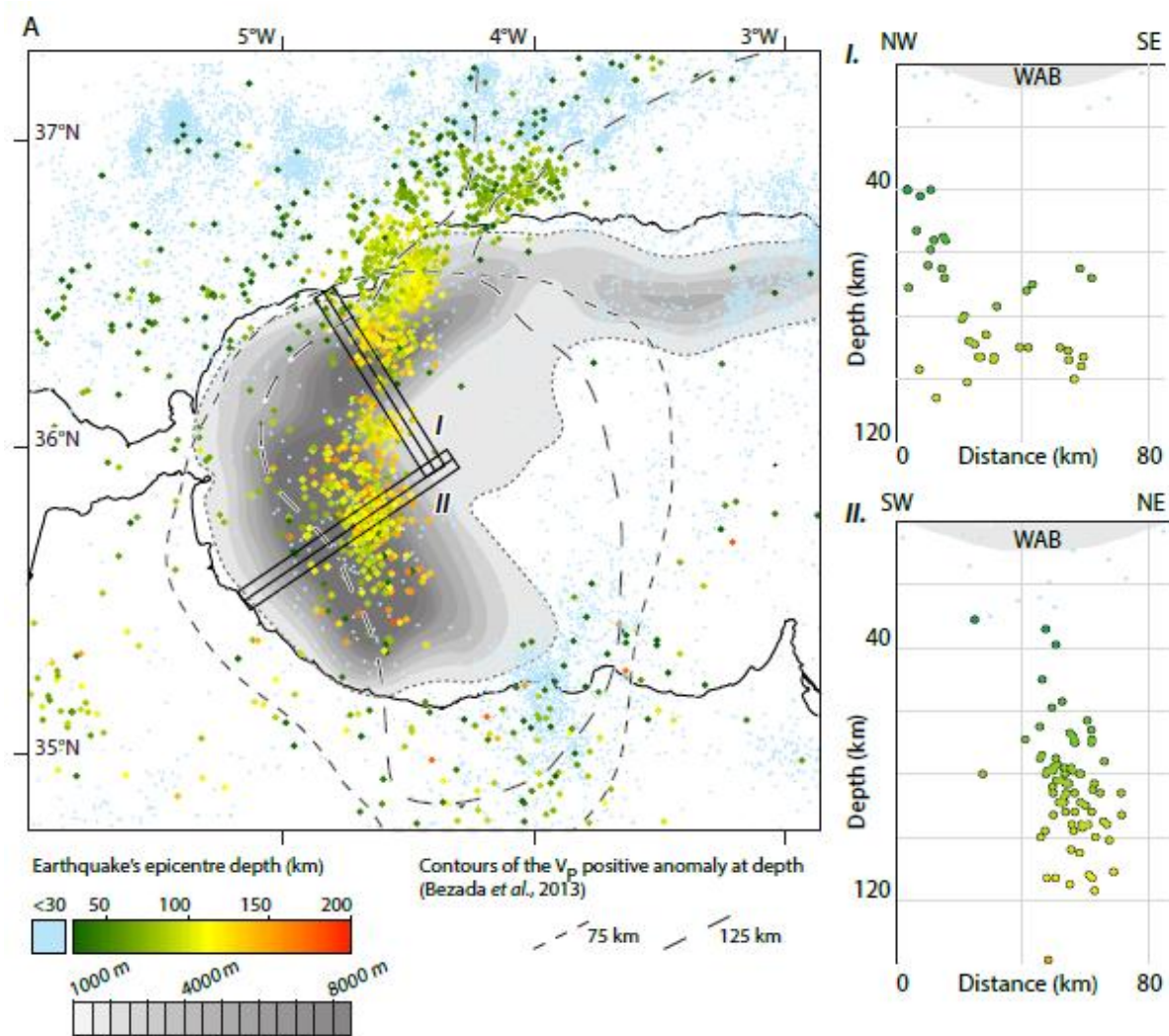


Figure 3

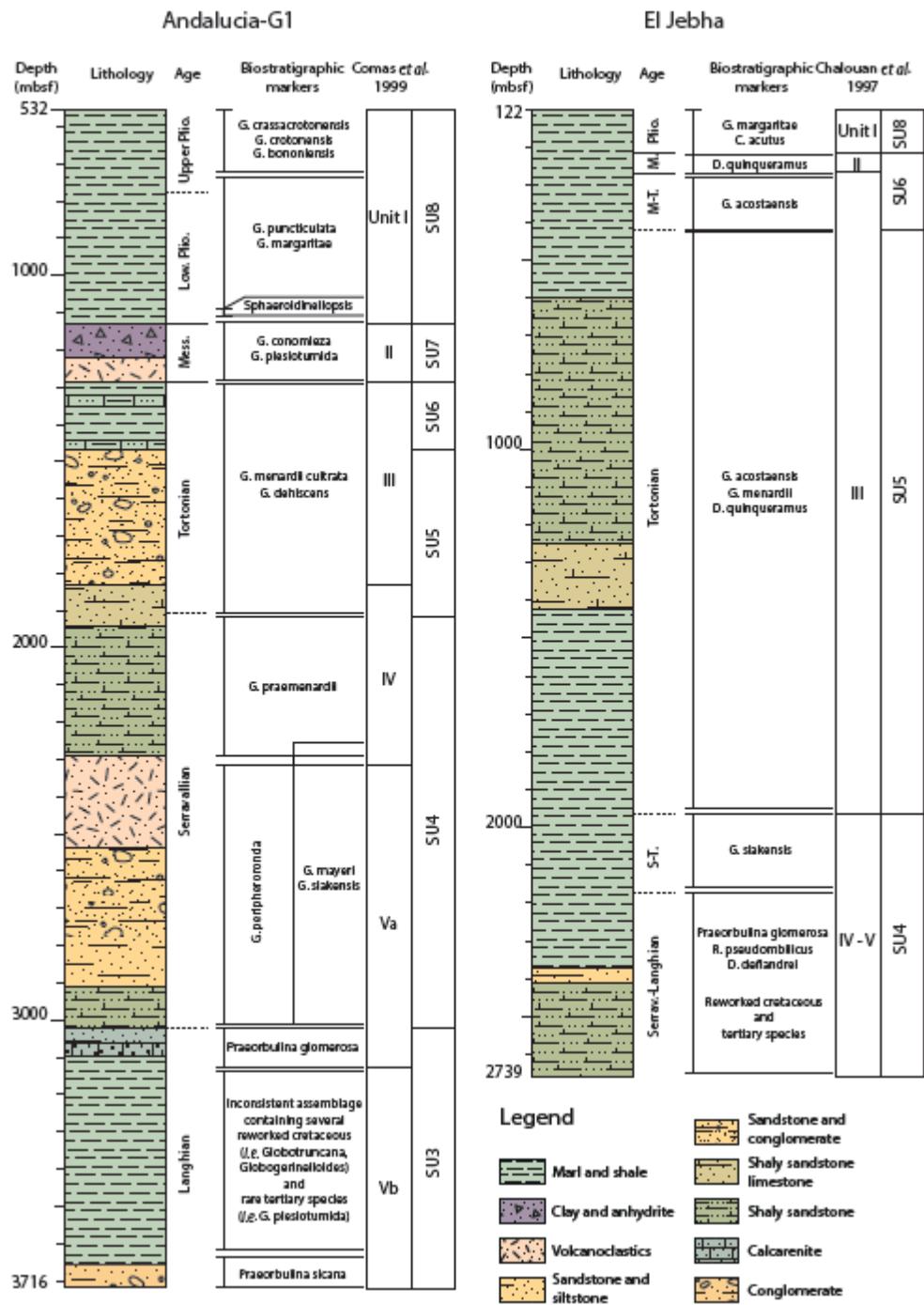


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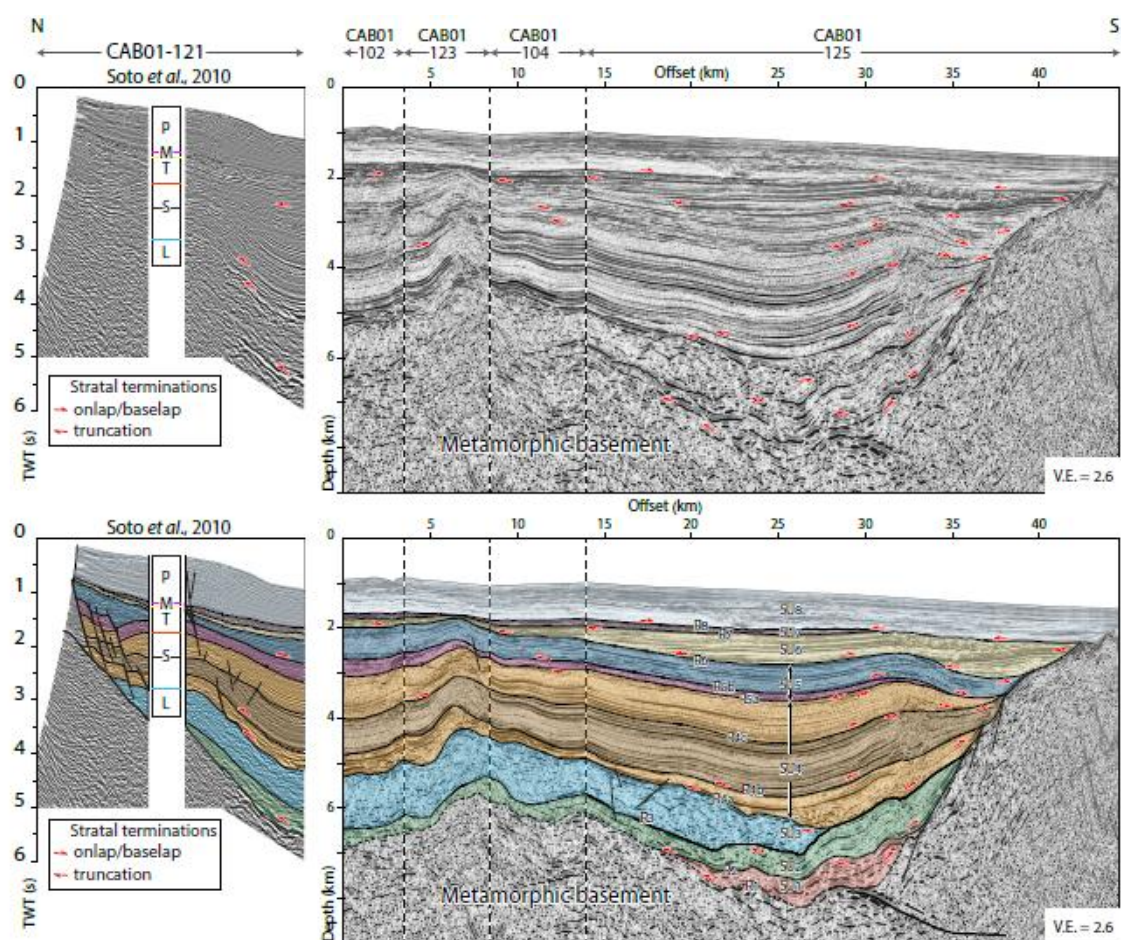


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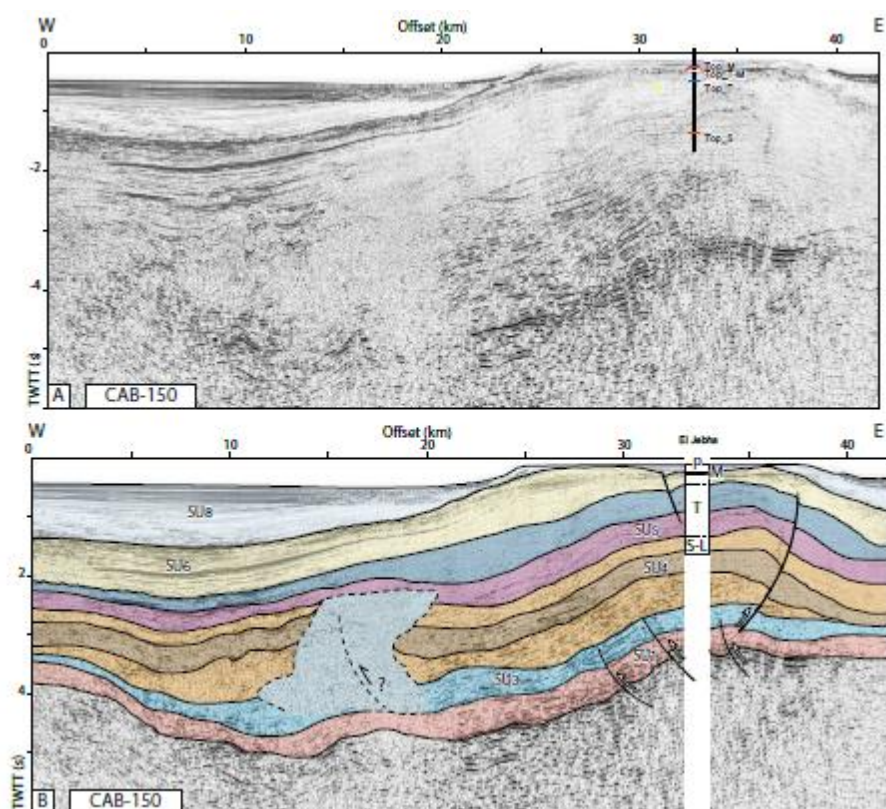


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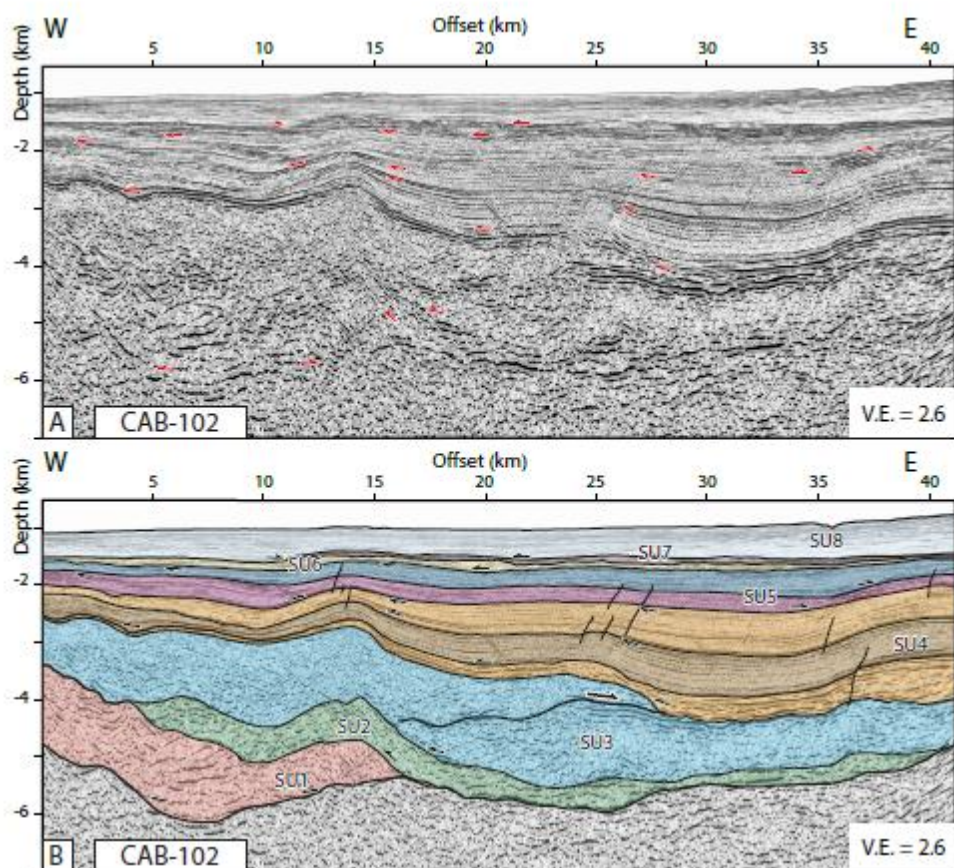


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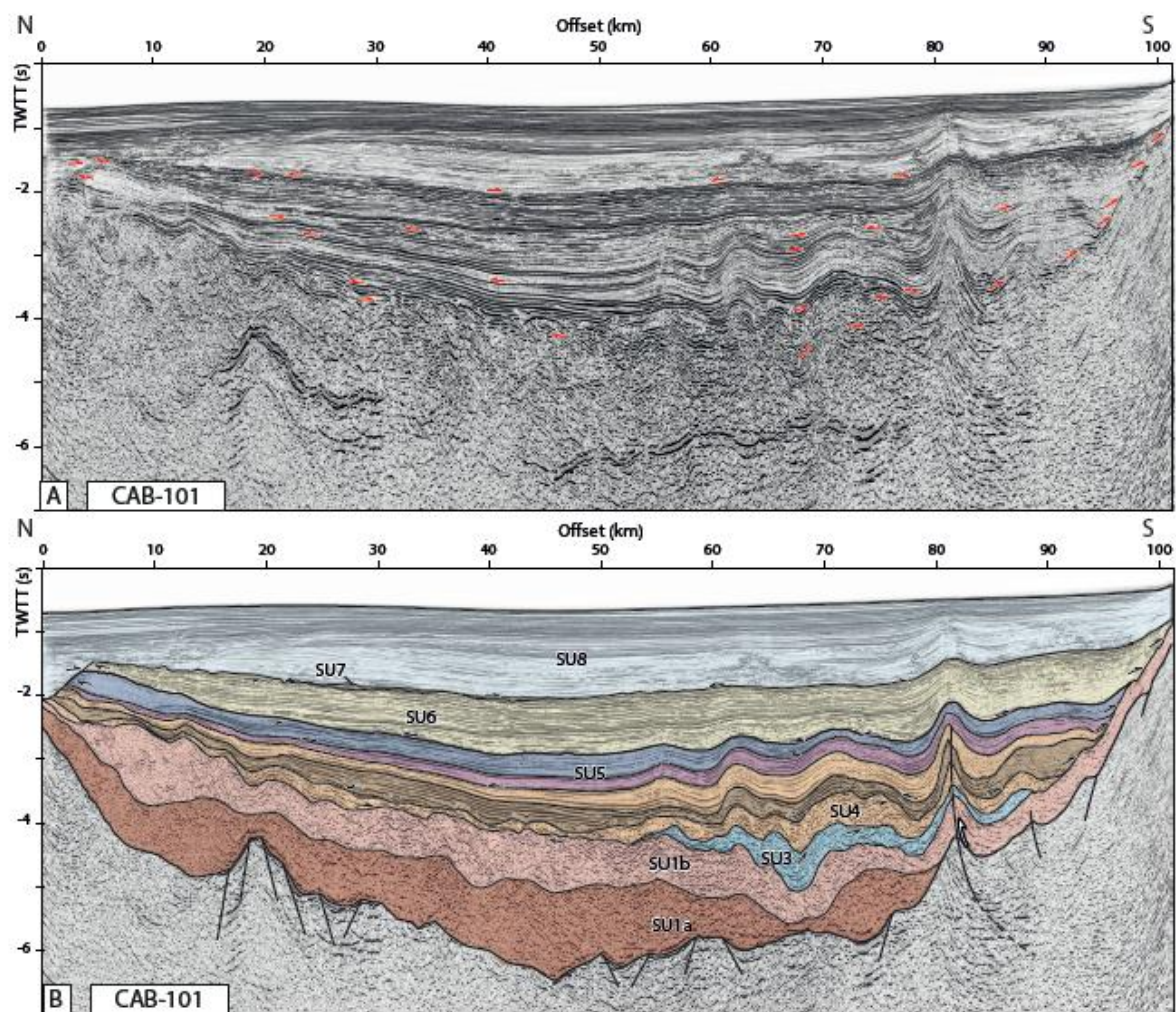


Figure 8

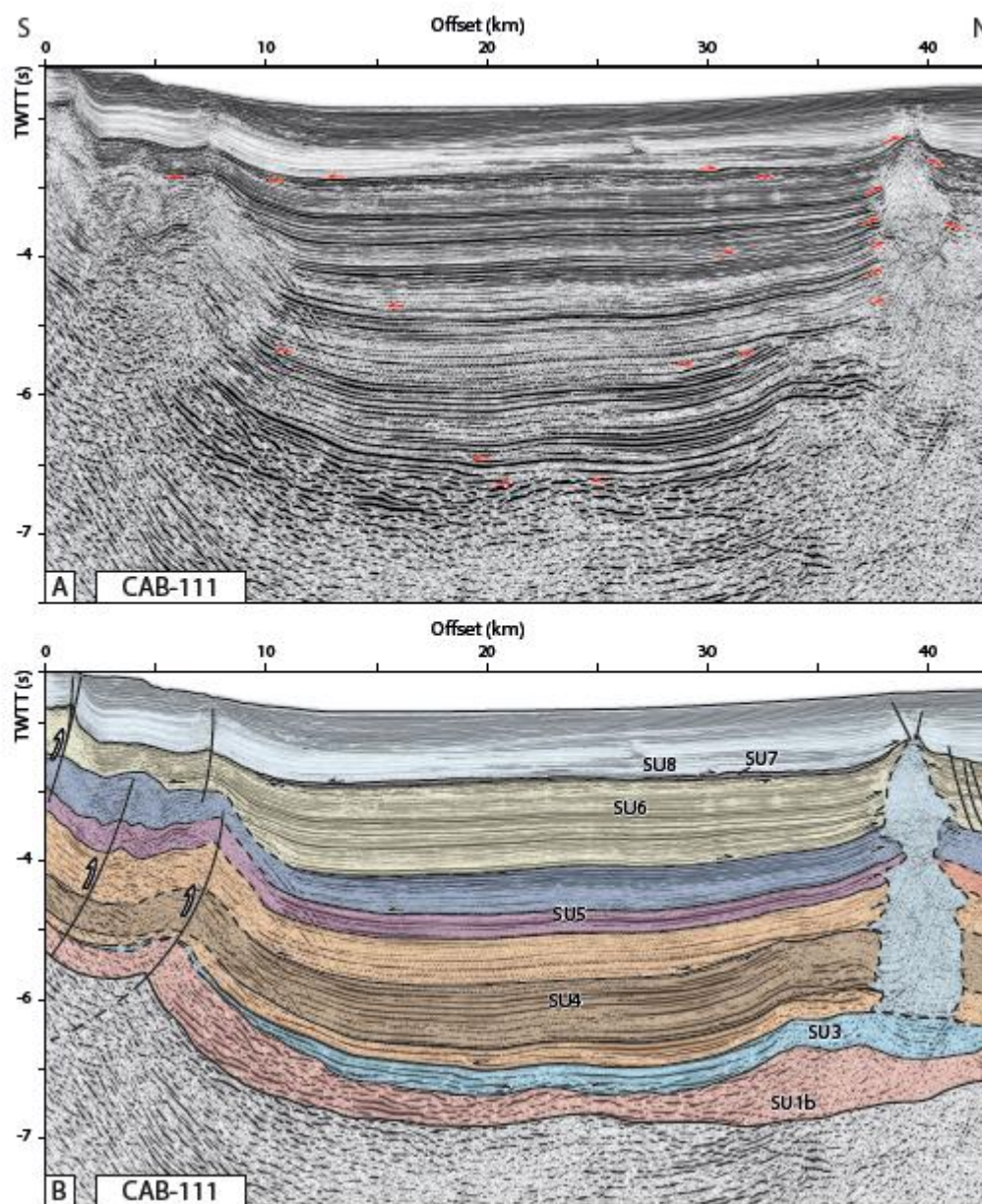


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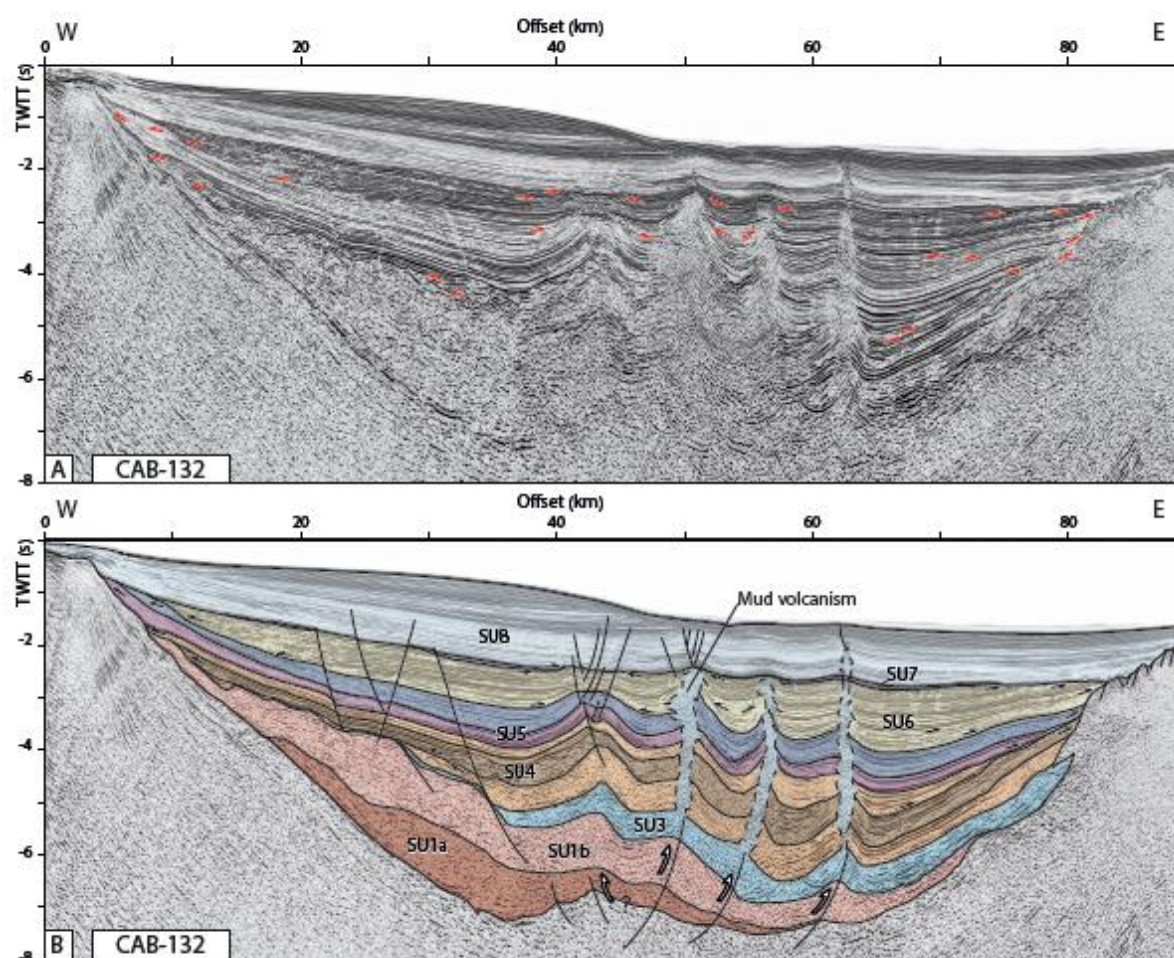


Figure 10

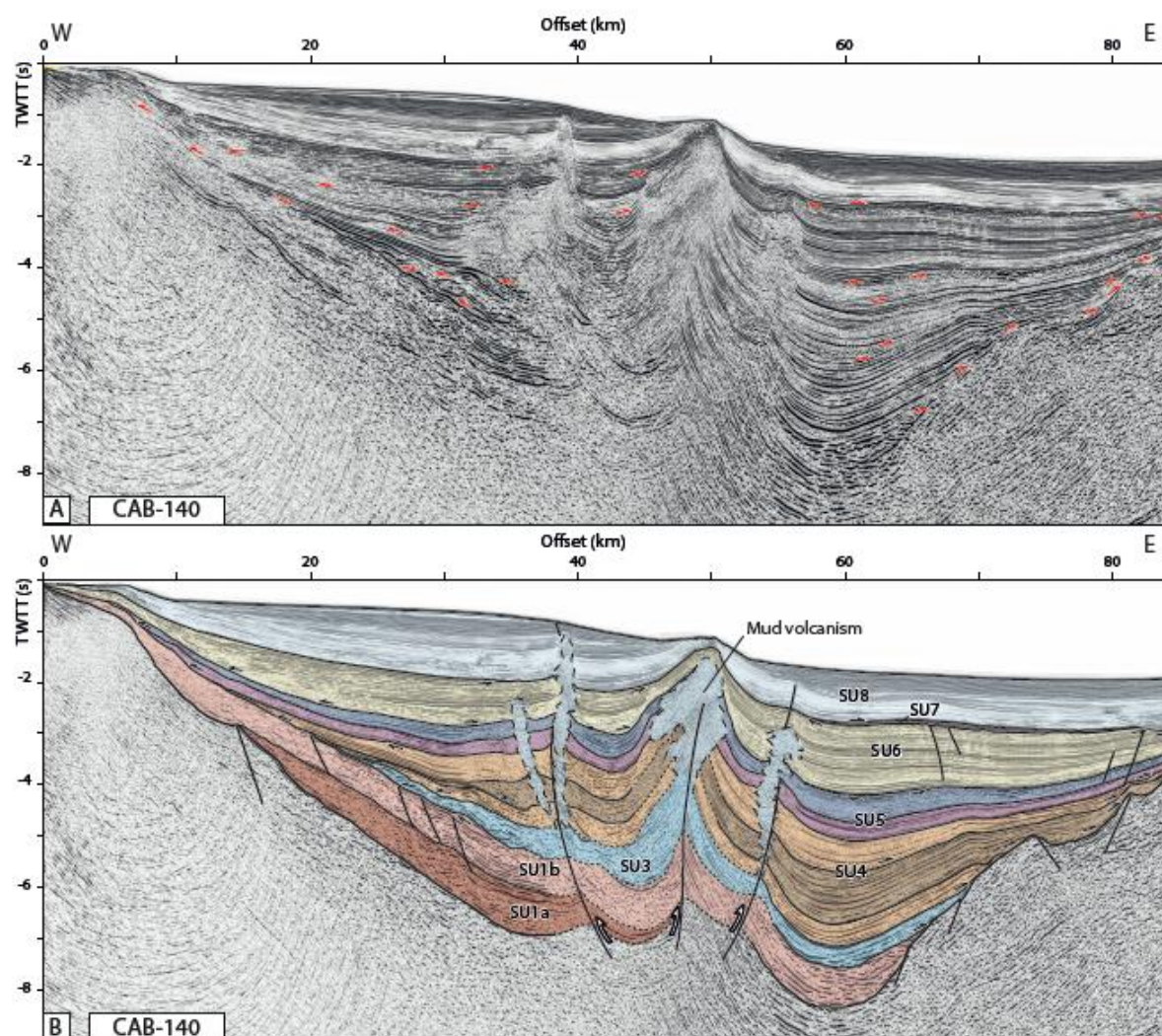


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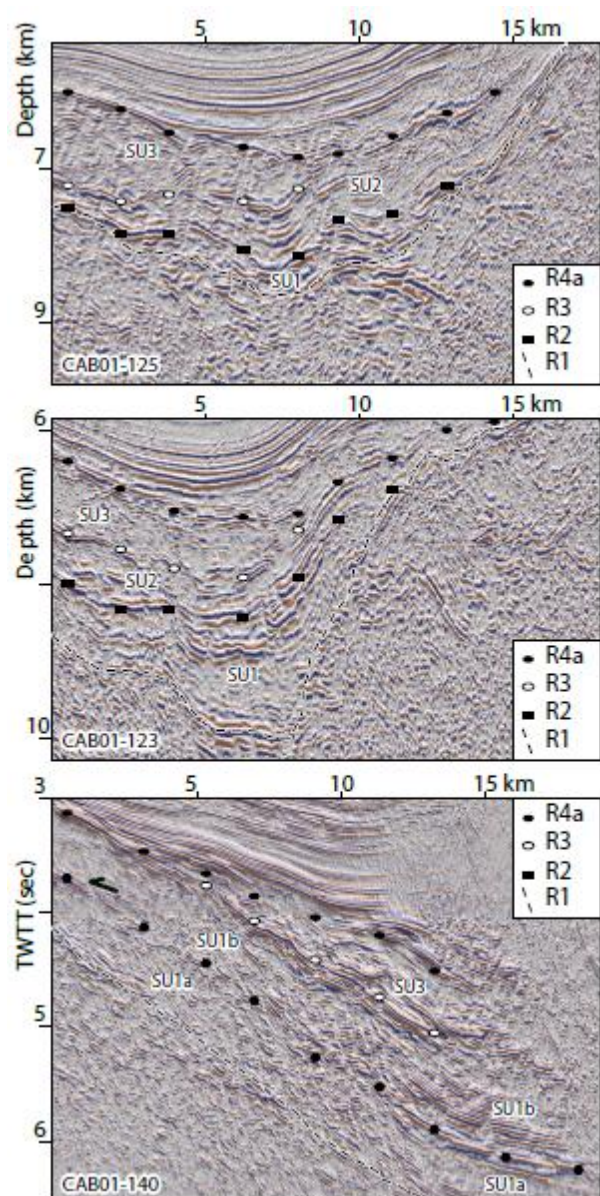


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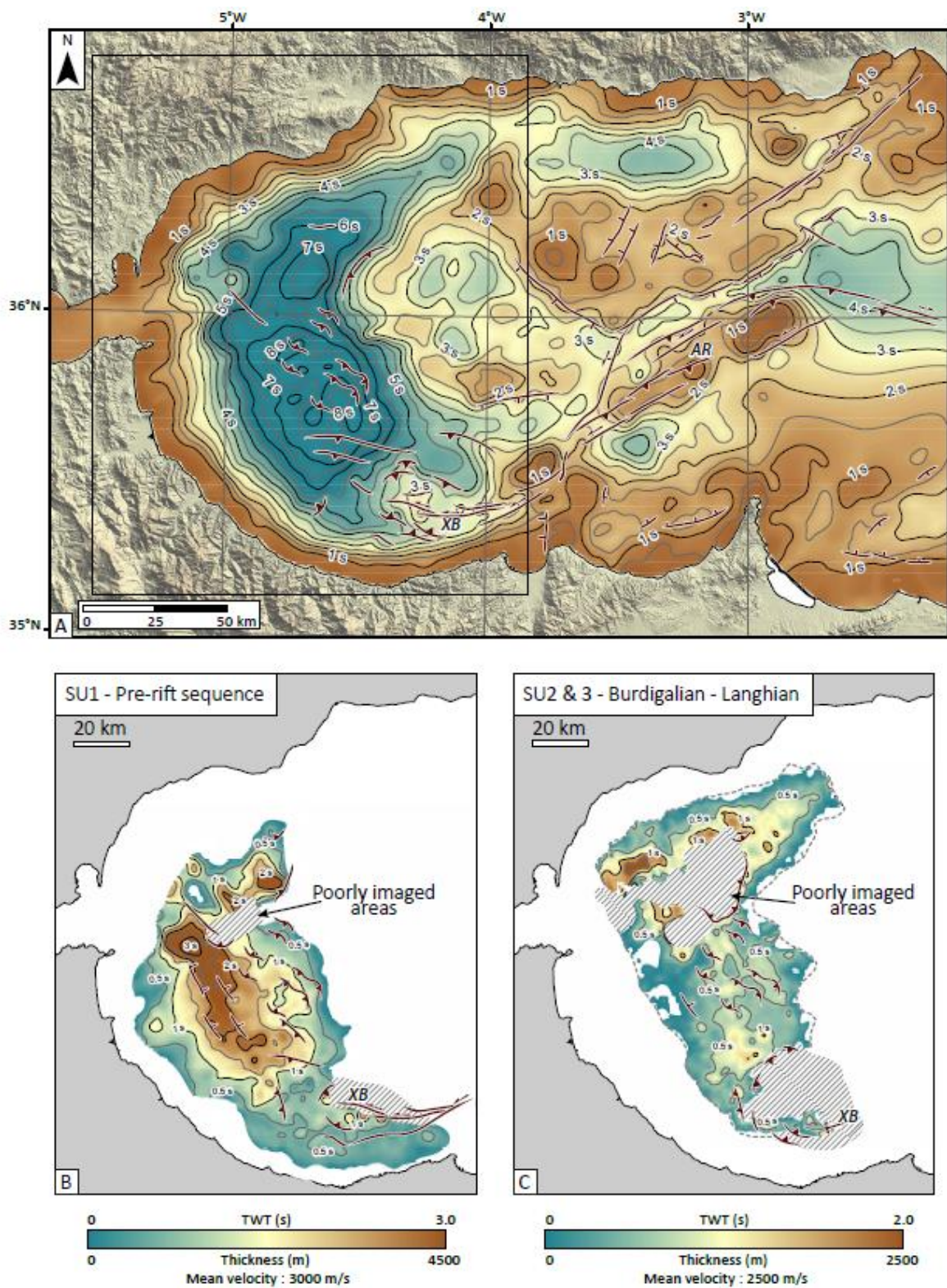


Figure 13

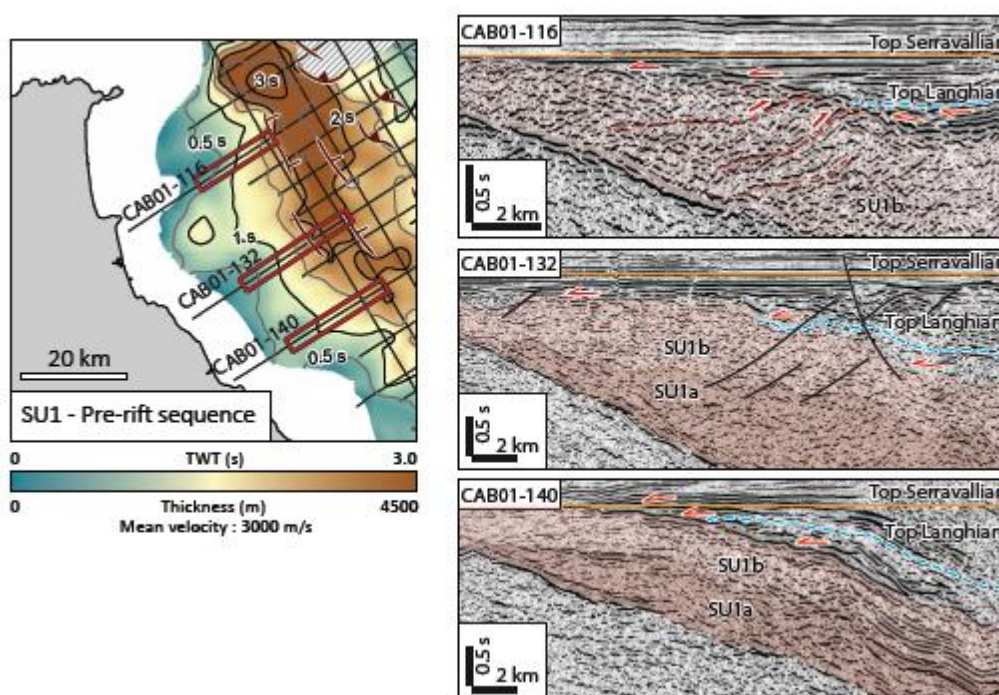


Figure 14

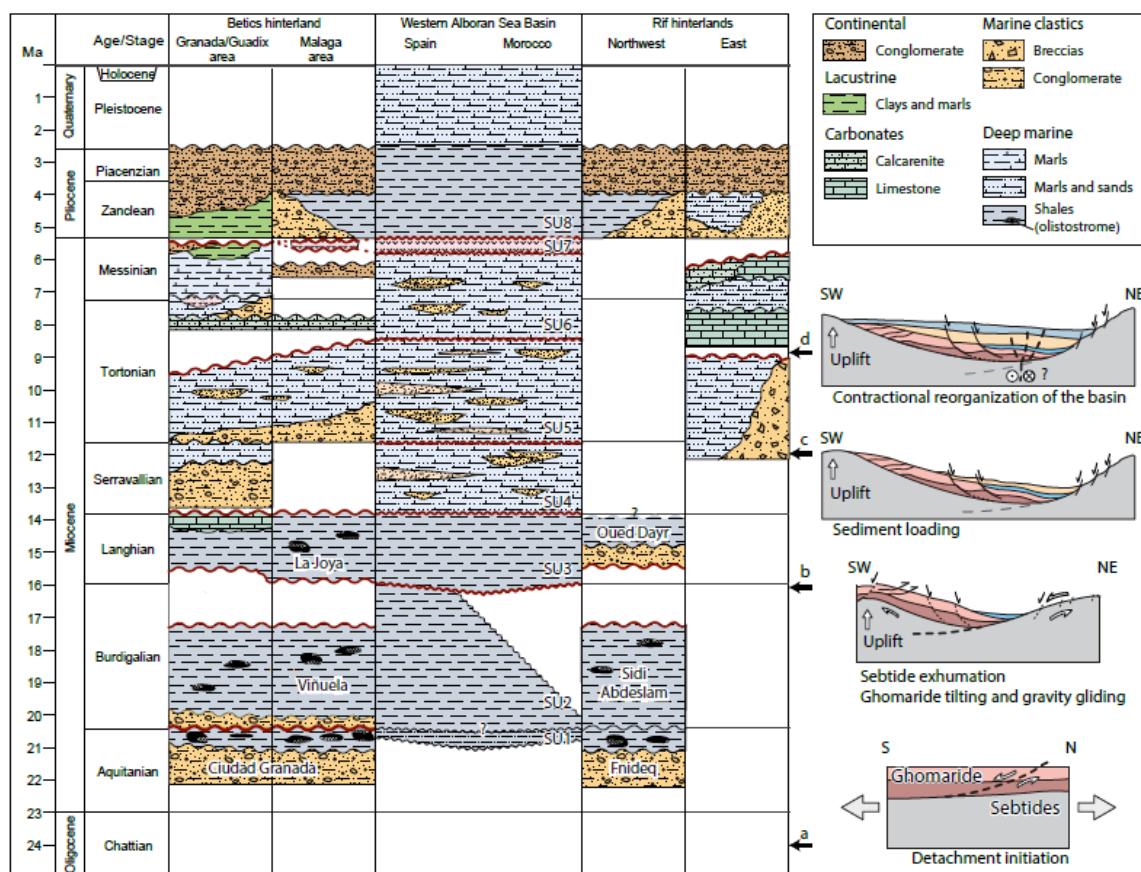


Figure 15

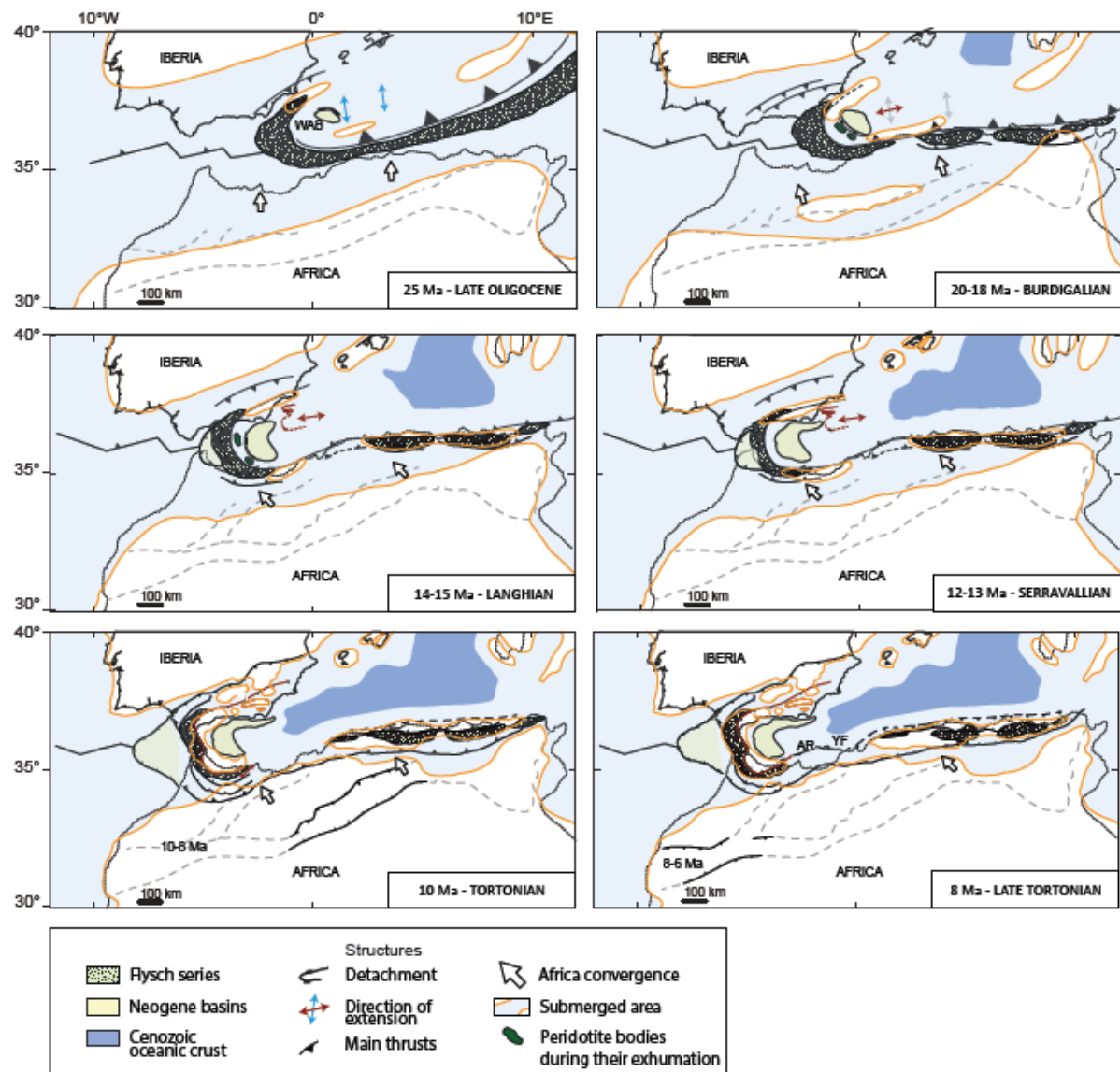


Figure 16

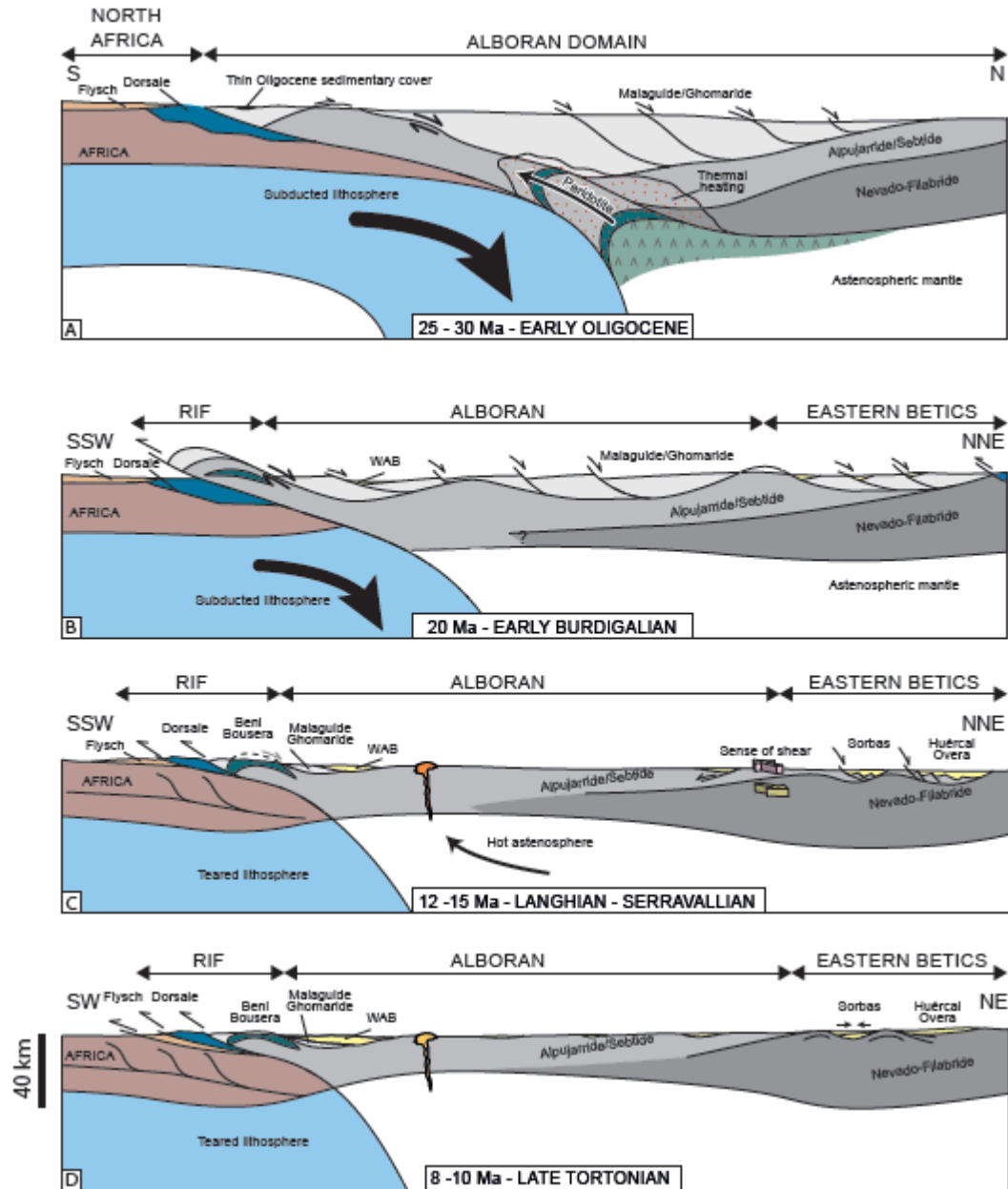


Figure 17

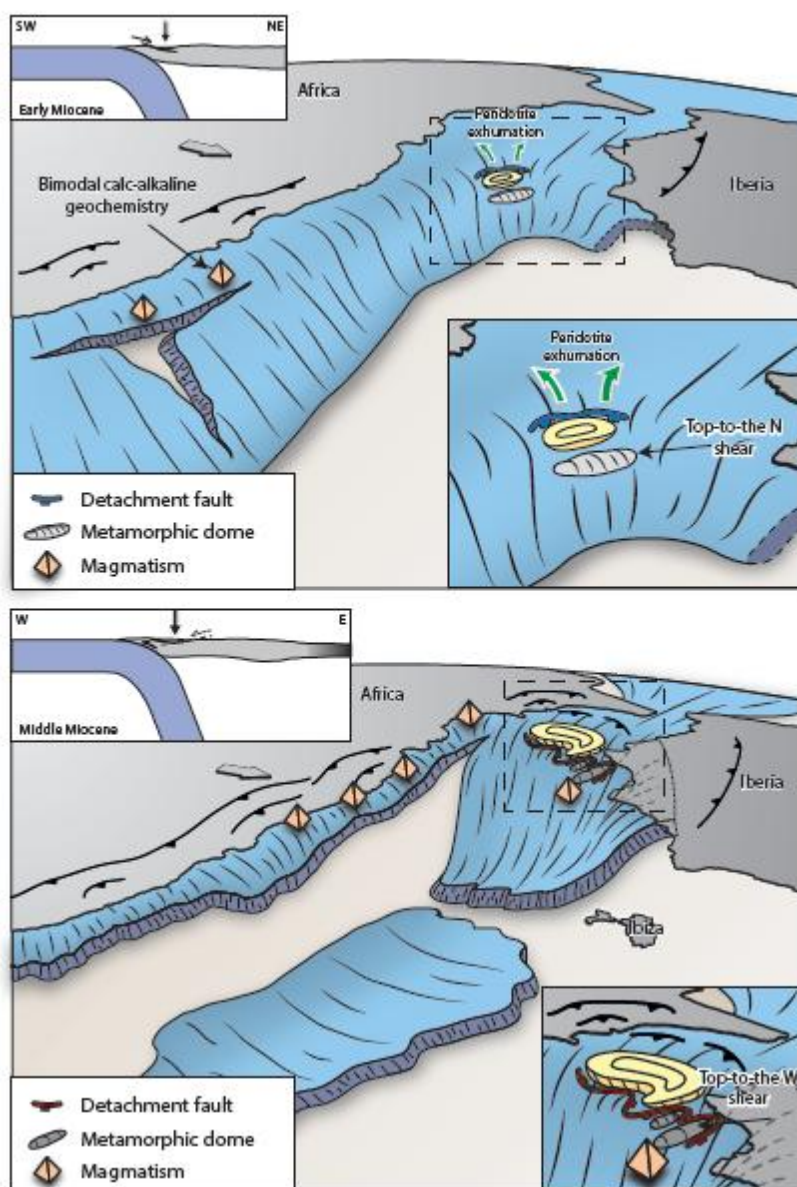


Figure 18

## Highlights

- Stratigraphic analysis of high-resolution 2D seismic allow to clarify the tectonic and stratigraphic history of the WAB.
- A three step tectonic and stratigraphic scenario is proposed based on the seismic interpretation and onshore correlations: a first subsidence pulse was probably controlled by extensional detachment; then a vertical subsidence marks a sag behavior of the WAB before its tectonic inversion in the last 10 Myrs.
- We explain that the subsidence of the WAB was controlled by the load of the dipping subducting lithosphere.