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Evidence for transform motion along the South Balearic margin and implications for the kinematics of opening of the Algerian basin

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Keywords. – South Balearic margin, Algerian basin, Seismic reflexion profiles, Gravity models, Magnetic anomalies, Kinematics, Transform margin.

Abstract. – Two major types of kinematic models have been proposed to explain the opening of the western Mediterranean basins (Liguro-Provençal and Algerian basins, and Valencia trough). In one type of models, all continental blocks bounding the basins drift to the southeast, driven by the rollback of the Tethys subduction slab. In the other type of models, the Alboran domain drifts to the southwest, implying a westward rollback of the broken subducting slab and a NE-SW opening of the Algerian basin. In most models, however, the structure of the Balearic promontory was not taken into account, despite its key location at the boundary of the three major basins. We used the interpretation of a large seismic database coupled to gravity and magnetic anomaly analyses to characterize the nature and structure of the South Balearic margin. The constraints brought by the new analyses allow us to suggest a new scenario for the opening of the Algerian basin.

Seismic profiles show that the South Balearic margin is composed of four segments with different morphologies and crustal structures. Two segments, the Mazarron and the Emile Baudot escarpments, are characterized by steep scarps and sharp crustal thinning. Two other segments, the South Ibiza and South Menorca margins, have a smoother bathymetry and crustal thinning. We interpret the former in terms of transform margins, and the latter as divergent margins. The distribution of faults on the passive margin segments suggests that they have recorded at least two phases of deformation. A first phase of opening, probably in a NW-SE direction, affected the south Balearic margin, and possibly created some oceanic floor. The existence of the transform margin segments and the prominent NW-SE orientation of the magnetic lineations in the eastern Algerian basin suggest that most of this basin opened in a NE-SW direction, in different oceanic corridors. The two eastern corridors formed by the southwestward drift of the Kabylies. The western corridor, bounded by the transform segments of the South Balearic margin and the Algerian margin, results from the southwestward drift of the Alboran domain, as suggested by previous studies.

Evidences d'un mouvement transformant le long de la marge Sud-Baléares et implications pour la cinématique d'ouverture du Bassin algérien

Mots-clés. – Marge Sud-Baléares, Bassin algérien, Profils sismiques, Modèles gravimétriques, Anomalies magnétiques, Cinématique, Marges transformantes.

Résumé. – Deux grands types de modèles cinématiques ont été proposés pour expliquer l'ouverture des bassins de la Méditerranée occidentale (bassins Liguro-Provençal et Algérien et fossé de Valence). Dans un type de modèles, tous les blocs continentaux limitant les bassins dérivent vers le sud-est, tirés par le retrait de la subduction de la plaque téthysienne. Dans l'autre type de modèles, le domaine d'Alboran dérive vers le sud-ouest, impliquant un retrait vers l'ouest de la subduction d'une partie de la plaque téthysienne déchirée. Dans la plupart de ces modèles, cependant, le promontoire Baléares n'est pas pris en compte, et ce, malgré sa position clé à la frontière des bassins majeurs. Nous avons utilisé l'interprétation d'une large base de données sismiques couplée à une analyse des anomalies gravimétriques et magnétiques pour caractériser la nature et la structure de la marge Sud-Baléares. Les contraintes apportées par les nouvelles analyses nous permettent de proposer un nouveau scénario pour l'ouverture du Bassin algérien.

La sismique réflexion montre que la marge Sud-Baléares est composée de quatre segments qui diffèrent en termes de morphologie et de structure. Deux segments, les escarpements de Mazarron et d'Emile Baudot, sont caractérisés par des escarpements abrupts ainsi que par un rapide amincissement crustal. Les deux autres, les marges au sud d'Ibiza et de Minorque, montrent une bathymétrie moins abrupte et un amincissement crustal plus progressif. Nous interprétons les deux premiers segments comme des marges transformantes et les deux derniers segments comme des marges divergentes. La distribution des failles sur les segments de marges divergentes suggère qu'elles ont enregistré au moins deux phases de déformation. Une première phase d'ouverture, probablement orientée NW-SE, a affecté la marge sud-Baléares et créé de la croûte océanique. L'existence de segments transformants et l'orientation clairement NW-SE des linéations magnétiques de l'est du Bassin algérien suggèrent que ce bassin s'est ouvert principalement suivant une direction NE-SW, formant différents corridors océaniques. Nous proposons que les corridors de l'est du bassin se soient formés par une dérive vers le sud-ouest des Kabylies. Le corridor ouest, limité par les segments transformants de la marge Sud-Baléares et par la marge algérienne, résulte de la dérive vers le sud-ouest du domaine d'Alboran, comme suggéré par des études précédentes.

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INTRODUCTION

The western Mediterranean is a complex area composed of several basins, floored by oceanic (Liguro-Provençal, Algerian and Tyrrhenian basins) or thinned continental lithosphere (Valencia trough, West Alboran basin), surrounded and separated by thrust belts (Betic-Rif, Tell, Apennines, Alps) (fig. 1). This complex setting results from the interaction between orogenic and extensional processes, within the framework of the convergence between Africa and Eurasia. A large number of local and regional studies, and reconstruction models of the evolution of the western Mediterranean, have been presented in a vast literature. It is commonly accepted that widespread extension started in Oligocene time when the convergence between Africa and Eurasia slowed down and the northward subduction of the old oceanic Tethys lithosphere started to retreat [e.g., Tapponnier, 1977; Malinverno and Ryan, 1986; Royden, 1993; Lonergan and White, 1997]. Back-arc extension led to the fragmentation of the Mesozoic-Early Cenozoic Alpine orogenic belt into different continental blocks [Bouillin *et al.*, 1986], whose migration allowed for the opening of the Neogene basins [e.g., Rehault *et al.*, 1984].

The nature of the crust in the different basins has been partly constrained by geophysical studies, and the motion of continental blocks by paleomagnetic measurements. The location of subduction zones has been evidenced by the associated volcanism, the seismicity, and the seismic tomography. Based on these observations, two types of models of palinspastic reconstructions have been proposed for the western Mediterranean (fig. 2). All models agree on two points: (1) the NW-SE opening of the Liguro-Provençal basin, with the counterclockwise rotation of Corsica and Sardinia; (2) the important role of the North Balearic fracture zone [Mauffret *et al.*, 1995], located east of Menorca and representing the boundary between the Valencia trough or the Algerian basin to the west and the Liguro Provençal basin to the east (fig. 1). The models differ on the kinematics of opening of the Algerian basin and the behavior of the retreating subduction. The first type of models (fig. 2a) suggests that the Valencia trough, the Liguro-Provençal and the Algerian basins opened in a similar, ~NW-SE direction, at different times [Boccaletti and Guazzone, 1974; Rehault *et al.*, 1984; Gueguen *et al.*, 1998; Vergès and Sabàt, 1999; Zeck and Whitehouse, 1999; Rosenbaum and Lister, 2004; Guerrera *et al.*, 2005; Schettino and Turco, 2006; Vergès and Fernandez, 2012; Carminati *et al.*, 2012]. The Liguro-Provençal basin and the Valencia trough formed in the late Oligocene-early Miocene as a result of the eastward roll-back of the Calabrian slab and the rotation of the Corso-Sardinian block (CSB) [Rehault *et al.*, 1984; Gattacecca *et al.*, 2007]. The Algerian basin opened in the middle Miocene due to the southward migration of the Maghrebian trench. This type of models does not suggest any westward motion of continental block [Rehault *et al.*, 1984; Vergès and Sabàt, 1999; Zeck and Whitehouse, 1999; Guerrera *et al.*, 2005; Schettino and Turco, 2006; Vergès and Fernandez, 2012] or a very limited westward motion compared to the southward one [Facenna *et al.*, 2004; Jolivet *et al.*, 2008]. In the second type of models (fig. 2b), the Valencia trough and the Liguro-Provençal basins open in a NW-SE direction, but the Algerian basin opens in a NE-SW or E-W direction, as a result of the westward drift of the Alboran domain driven by the westward-retreating Gibraltar slab [Andrieux *et al.*, 1971; Frizon de Lamotte *et al.*, 1991, 2000, 2008; Rosenbaum *et al.*, 2002; Mauffret *et al.*, 2004; Spakman and Wortel, 2004; Bezada *et al.*, 2013; Medaouri *et al.*, 2014; Van Hinsbergen *et al.*, 2014] or dragged by a mantle flow [Mattauer, 2007]. Some of these models also include an episode of N-S extension [Frizon de Lamotte *et al.*, 1991, 2000, 2008; Rosenbaum and Lister, 2004].

While many studies have been conducted in the Liguro-Provençal basin and the Alboran sea, the Algerian basin and Balearic promontory have been less surveyed. Interestingly, most geodynamic models do not clearly deal with the opening of the eastern Algerian basin [Biju-Duval *et al.*, 1978; Lonergan and White, 1997; Gueguen *et al.*, 1998; Michard *et al.*, 2006; Jolivet *et al.*, 2009; Carminati *et al.*, 2012]. The regional kinematics and chronology of opening of this area are still debated. Understanding the nature of the south Balearic margin is a key question to constrain the kinematics of the Algerian basin. In particular, the different models imply either divergent or transform motion along the southern margin of the promontory. Constraining the motion along this margin thus helps choose between the two types of kinematic models. We present a study of the Balearic promontory, using a large set of seismic reflexion profiles, as well as models of gravity anomalies across the margins, to describe its morphology, crustal structure and deformation. Our analysis leads to a new interpretation of the south Balearic margin. We include the observations of the magnetic anomaly lineations in the Algerian basin in the analysis, because they constrain the kinematics of the eastern Algerian basin. The compilation of these observations allows us to suggest a new reconstruction of this part of the western Mediterranean basin, which is more consistent with all geological and geophysical data.

REGIONAL GEOLOGICAL AND GEODYNAMICAL SETTINGS

The western Mediterranean sub-basins

The Balearic promontory separates the Valencia trough from the Algerian basin, and is bounded to the east by the Liguro-Provençal basin. These basins have distinct morphologies and structures. They also have different histories, which have partly been shared with that of the Balearic promontory.

The Liguro-Provençal basin is floored by stretched continental crust and oceanic crust narrowing to the northeast (fig. 1) [Bayer *et al.*, 1973; Le Douaran *et al.*, 1984; Burrus, 1984; Chamot-Rooke *et al.*, 1999]. It is limited to the southwest by the North Balearic fracture zone [e.g., Maillard *et al.*, 1992]. It results from the rotation of Corsica with respect to Provence, and of Sardinia with respect to the gulf of Lions, during the Oligo-Miocene (23-15 Ma) [Rehault *et al.*, 1984; Speranza *et al.*, 2002; Gattacceca *et al.*, 2007].

The Valencia trough (fig. 1) is formed by stretched continental crust with widespread volcanism [Pascal *et al.*, 1992; Torné *et al.*, 1992]. It has been interpreted to be an aborted Oligo-Miocene continental rift [Gelabert *et al.*, 1992; Maillard *et al.*, 1992; Mauffret *et al.*, 1992, 2004]. A second phase of volcanism occurred from the Late Miocene

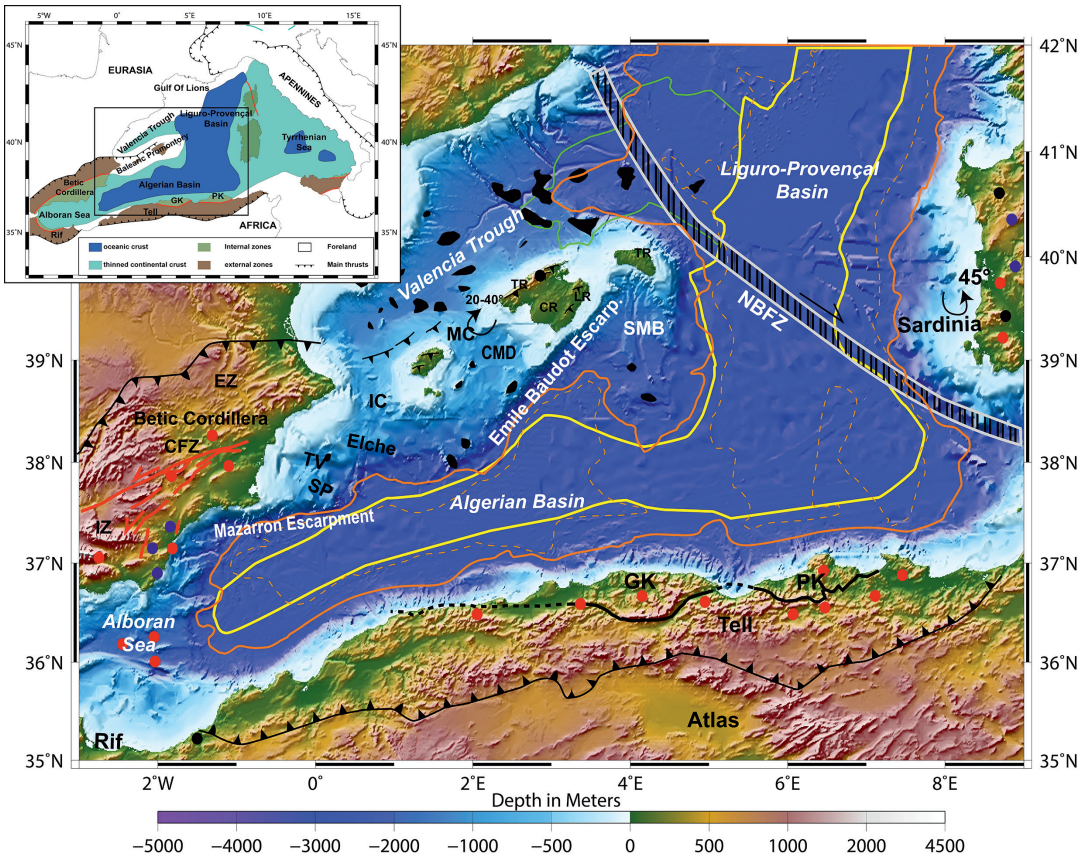

FIG. 1. – Bathymetric map of the Balearic area and major geological features of the basins and surrounding thrust belts. Black shapes are volcanic areas [from Maillard *et al.*, 1992]. Arrows show paleomagnetic rotations [from Parès *et al.*, 1992; Rehault *et al.*, 1984 and Gattacceca *et al.*, 2007]. Thick yellow line is ocean-continent boundary; thin green line is continent-transition crust boundary [both from Mauffret *et al.*, 1995 and Mascle *et al.*, 2012]. Blue, red and black dots are Late Miocene, Middle Miocene and Oligocene-early Miocene volcanics, respectively [from Rosenbaum *et al.*, 2002 and Carminati *et al.*, 2012]. Orange solid line marks the extension of the Messinian halite, and orange dashed line that of the diapirs [from Lofi *et al.*, 2011). TR: Tramuntana ranges; LR: Llevant ranges; CR: Central ranges; TV: TorreVieja half graben; SP: San Pedro basin; SMB: South Menorca block; CFZ: Crevillente fault zone; EBE: Emile Baudot escarpement; NBFZ: North Balearic fracture zone [from Gueguen *et al.*, 1998]; IC: Ibiza channel; CMD: Central Mallorca depression. IZ: Internal zone; EZ: External zone; GK: Grande Kabylie; PK: Petite Kabylie. (*Colors refer to PDF version*).

to the Quaternary, especially along the transfer zones [Rivière *et al.*, 1981; Marti *et al.*, 1992; Maillard and Mauffret, 1993, 1999].

The Algerian basin is narrow in the west, widening in its eastern part, and is almost entirely covered by a thick layer of Messinian evaporites, including 1500 m of halite (fig. 1). Refraction profiles show that the crust in the Algerian basin is 5.5 to 6 km thick and is oceanic in nature [e.g., Vidal *et al.*, 1998; Catalano *et al.*, 2000; Hübscher *et al.*, 2010]. Moreover, they display an abrupt crustal thinning across the Mazzaron and Emile Baudot scarps, while the thinning is more progressive in the Ibiza channel [Hübscher *et al.*, 2010]. The western and eastern parts of the basin are separated, south of Menorca island, by a basement high called the Hannibal ridge, and interpreted to be a relict oceanic spreading center by Mauffret *et al.* [1995, 2004].

The Alboran sea and the adjacent Betic-Rif belt result from the westward motion of the Alboran domain, still active today [Bouillin *et al.*, 1986; Frizon de Lamotte *et al.*, 1991; Lonergan and White, 1997; Mauffret *et al.*, 2004; Duggen *et al.*, 2008; Gutscher *et al.*, 2002, 2012]. The crustal nature of the Alboran sea is similar to the internal zone of the Betics observed on land [Platt and Vissers, 1989; Comàs *et al.*, 1996]. The central Alboran sea displays mainly Miocene tholeiitic magmas and the surrounding area (western Alboran) displays Miocene calc-alcaline magmas [Duggen *et al.*, 2008]. These observations are consistent with the presence of an eastward-dipping slab retreating westward.

Africa is currently converging toward Eurasia at a rate of 5 mm/yr [DeMets *et al.*, 1990; Nocquet and Calais, 2003; Serpelloni *et al.*, 2007]. The deformation is mainly localized in the thrust belts of North Africa. It appears to affect the Balearic promontory only west of Ibiza [Serpelloni *et al.*, 2007]. This region shows recent strike-slip and normal faults, as well as numerous mass-wasting structures [Acosta *et al.*, 2002, 2004a, 2004b; Lastras *et al.*, 2004; Camerlenghi *et al.*, 2009; Maillard and Mauffret, 2013]. The thrust belts surrounding the western Mediterranean basins (Betics, Rif, Tell) result mainly from the closure of the old Tethysian oceanic domain. The associated subducting slabs are observed in the seismic tomography images, and in the distribution of the earthquakes [e.g., Spakman and Wortel, 2004; Serpelloni *et al.*, 2007; Van Hinsbergen *et al.*, 2014].

The Balearic promontory

The Balearic promontory is a 400 km-long, 110 km-wide, NE-SW-trending continental high (fig. 1). It includes four major islands: Ibiza and nearby Formentera, Mallorca and Menorca, surrounded by a shallow (100 m deep) and narrow continental platform, and separated by two lows: the Ibiza channel between mainland Spain and Ibiza and the Mallorca channel between Mallorca and Menorca islands (IC and MC on fig. 1). Of the two bathymetric lows, the Ibiza channel is the deepest (800 m) and widest (25 to 45 km) [Acosta *et al.*, 2001; Acosta *et al.*, 2013]. The Mallorca channel includes the Central Mallorca depression [Acosta *et al.*, 2004a], which is limited to the south by the crest of the Emile Baudot escarpment (EBE). The northern Balearic margin is a NE-SW-trending steep scarp. The southern Balearic margin displays four segments: two very steep scarps, Mazarron and Emile Baudot, and two more gently-deepening segments in the Ibiza channel and the South Menorca block (SMB). The southeastward continuation of the SMB is the basement high described as the Hannibal ridge [Mauffret *et al.,* 1995, 2004]. The eastern boundary of the Balearic promontory east of the SMB is the North Balearic fracture zone (NBFZ).

The Balearic promontory is one of the small continental blocks which detached from the Eurasian margin behind the retreating Tethysian subducting slab: the Corsica, Sardinia and Balearic islands and the AlKaPeCa blocks [Alboran-Kabylies-Peloritan-Calabria, Bouillin *et al.*, 1986]. It is thus the result of the complex interaction of both shortening and extensional events during the Miocene. It underwent Oligo-Miocene extension related to the formation of the Valencia trough, but also thrusting related to the formation of the external Betic-Rif belt, an Oligocene to middle Miocene thrust belt extending from the Gibraltar arc to the Balearic promontory [Bourrouilh, 1973; Ramos Guerrero *et al.*, 1989; Sanz de Galdeano *et al.*, 1990; Fontboté *et al.*, 1991, Roca, 2001; Sabàt *et al.*, 2011] (fig. 1). Observations on the Balearic islands, mainly on Ibiza and Mallorca Tramuntana, Central and Llevant ranges, show Mesozoic units thrusting Cenozoic units, along thrusts trending ESE-WNW with a top-to-the-northwest motion [Canals and Pujades, 1992; Durand-Delga and Fontboté, 1980; Fourcade *et al.*, 1982; Gelabert *et al.*, 1992, 2004; Sabàt *et al.*, 2011]. Offshore, Betic thrusts have also been observed north of Ibiza or Mallorca [Maillard *et al.*, 1992; Maillard and Mauffret, 1993; Roca and Guimera, 1992]. It is still debated whether the thrusts affect the whole margin [Roca and Guimera., 1992; Roca, 2001; Gelabert *et al.*, 1992] or stop near Mallorca [Maillard *et al.*, 1992; Mauffret *et al.*, 1992]. A paleomagnetic study showed that during this event the island experienced a clockwise rotation (fig. 1) [Parès *et al.*, 1992].

The Balearic promontory then underwent a post-orogenic extensional event from the late Serravalian [Cespedes *et al.*, 2001] to Recent, associated to a second clockwise rotation of the Promontory [Parès *et al.*, 1992]. This event led to the formation of Miocene basins outcropping on the different islands such as the Palma graben. It also affected the northern Balearic margin [Maillard *et al.*, 1992, 2014]. The main extension direction is WNW-ESE but locally a secondary axis is consistent with an ENE-WSW direction [Sabàt *et al.*, 2011]. Local compressional events occurred at the same time on Ibiza [Durand-Delga and Fontboté, 1980; Fourcade *et al.*, 1982] or on Menorca [Bourrouilh, 1973].

A NE-SW refraction profile along the Balearic promontory (blue stars on figure 3) [Banda *et al.*, 1980] shows that it consists of continental crust, with an average thickness of 22 km and velocities ranging from 6 km/s in the upper crust to 6.6 km/s in the lower crust. Banda *et al.* [1980] also suggest that the lower crust has a constant thickness of 10 km. Other models confirm this crustal structure and the rapid crustal thinning to the south [Ayala *et al.*, 2003; Schettino and Turco, 2006].

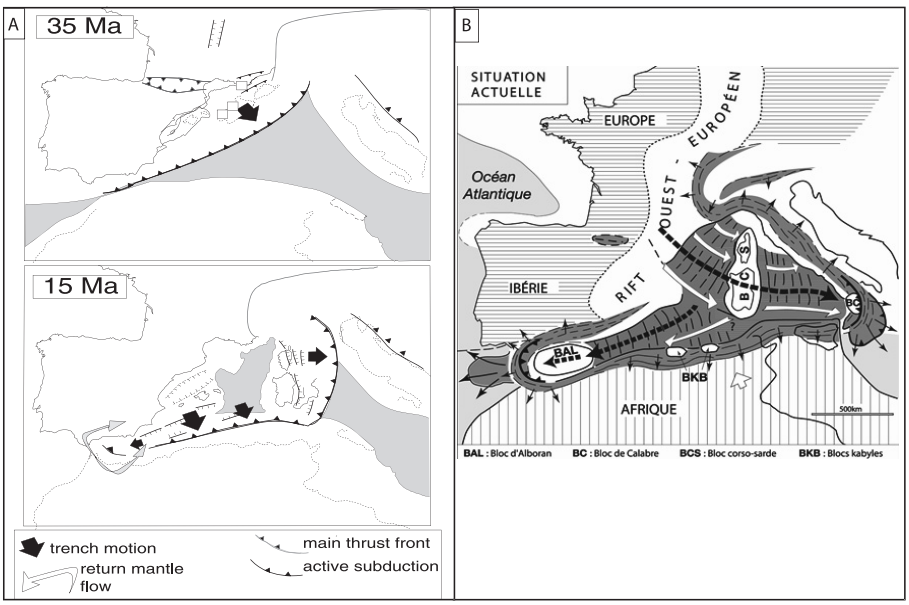

FIG. 2. – Illustrations of the two main types of models proposed for the opening of the western Mediterranean basin. A. General NW-SE opening [Zeck and Whitehouse, 1999]. B. Westward opening of the Algerian basin [Mattauer, 2007].

DATASETS AND METHODS

In order to study the shallow sedimentary and crustal structures of the margin, we analyzed a large seismic database (fig. 3). This database includes academic profiles from former cruises: BAL84 [Curzi *et al.*, 1985], VALSIS2 [Mauffret *et al.*, 1992; Torné *et al.*, 1992; Pascal *et al.*, 1992]. New academic lines have been added: CARBMED [Hübscher *et al.*, 2010; Just *et al.*, 2011], SIMBAD [Driussi *et al.*, 2014]. Industrial profiles include old data: RAY (Mandrel Industry, 1972), ALE (Total, 1974), Map (ENIEPSA, 1977), Meds (ENIEPSA, 1977) and SH (Sonatrach, 1977). Most of these old surveys can be found on the Spanish Geological Survey database: SIGEOF (www.igme.es). Most of the seismic profiles have been transformed from a tiff format associated with a navigation text file into SEG-Y format using the IMAGE2SGY software, a free SEG-Y tool developed at the Institute of Marine Sciences of Barcelona [Farràn, 2008]. The profiles have then been integrated into a Kingdom Suite project for comparison and interpretation.

For each profile, we distinguished the main horizons characterizing the structure of the margins: the seafloor, the base and top of the unit related to the Messinian Salinity Crisis (MSC), and the top of the acoustic basement. We then distinguished four seismic units based on their seismic facies, the most prominent facies being that of the Messinian unit:

– the Plio-Pleistocene unit (PP unit), above the MSC unit,

– the MSC unit, or its time equivalent Messinian erosion surface (MES), when MSC deposits are absent. The MSC unit consists of 2 sub-units, the MSC Upper Unit (UU) and the MSC Mobile Unit [MU, for the halite layer, Lofi *et al.*, 2011],

– the pre-MSC unit, which is mostly Miocene in age but possibly older (Oligocene),

– the acoustic basement, which is characterized by a chaotic facies, and represents either igneous rocks or Mesozoic sediment. This basement includes the pre-Cenozoic units. It sometimes displays internal horizons which must be related to the Mesozoic sediment, but most often the old sediment cannot be distinguished from igneous basement.

The seismic interpretations have been tied with the wells available in the region: DSDP sites 123, 122, 124 and 372 [Hsü *et al.*, 1973, 1978], ODP sites 973 and 975 [Comàs *et al.*, 1996] (green stars on figure 3) and industrial wells located on the eastern Spanish margin [Ochoa *et al.*, 2014]. The seismic interpretations were also adjusted to ensure consistency with published seismic lines at crossing points [Maillard *et al.*, 1992; Roca and Guimera, 1992; Sabàt *et al.*, 1997; Gallart *et al.*, 1994; Acosta *et al.*, 2001b; Just *et al.*, 2011]. All major faults and volcanic structures have been mapped. The seismic lines are presented in time sections. To convert the velocity in depths and compile the depth-to-basement map, we used a velocity of 1.5 km/s in the seawater, and the sediment velocity are from Maillard *et al.* [1992] based on the study of detailed depths versus time curves and data from wells and ESP [Pascal *et al.*, 1992].

In order to study the deep crustal structure and main crustal boundaries, we analyzed the magnetic anomalies [from Galdeano *et al.*, 1974; Galdeano and Rossignol, 1977], and the free-air gravity anomalies derived in the oceans from satellite altimetry [Bonvalot *et al.*, 2012] (fig. 3). We also performed 2-D modeling of the crustal structure along profiles across or along the Balearic promontory and the South Menorca block. The shallow structure in the models was constrained by our interpretations of seismic profiles, as well as by previously published seismic data. The deep structure was constrained by ESP [Pascal *et al.*, 1992] and some other refraction seismic profiles. Adjustment of the crustal structure along the models was performed using Geosoft Oasis Montaj GM-SYS. The density

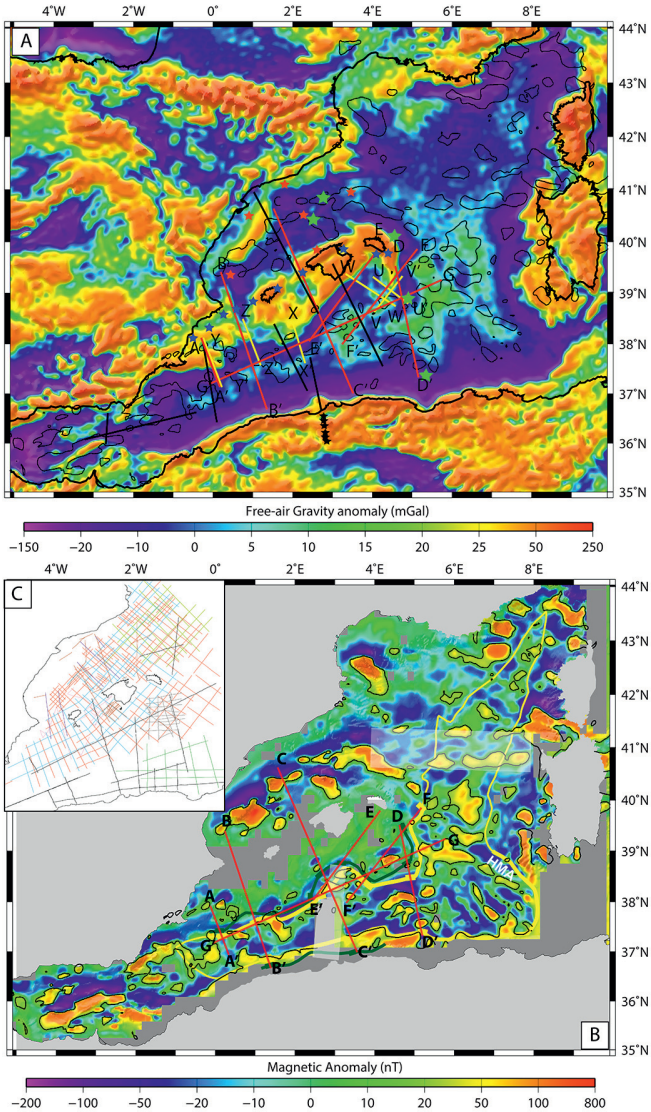

FIG. 3. – A. Free-air gravity anomalies [from Bonvalot *et al.*, 2012], showing crustal data. Black lines: ESCI profiles [Gallart *et al.*, 1994; Vidal *et al.*, 1998], Meteor profiles [Hübscher *et al.*, 2010], and Spiral profile (black stars on-shore) [Lepretre *et al.*, 2013]. Blue and yellow stars: Banda *et al.* [1980]. Red lines: gravity models from this study. Yellow lines: seismic profiles. B. Magnetic anomalies [from Galdeano and Rossignol, 1977]. Contours show magnetic values higher than 20 nT. The two white boxes highlight gaps between the original aeromagnetic surveys where anomalies have been interpolated from scarcer data points. The green line represents the boundary between continental and transitional crusts and the yellow one, the boundary between transitional and oceanic crusts. C. Location map of the seismic lines used for this study. (*Colors refer to PDF version*).

of each unit was calculated from the seismic velocities estimated from the refraction data (Banda, ESCI, ESP and the recent models from Ayala *et al.* [2003] or Schettino et Turco [2006]), using the "Nafe-Drake278 Curve" from Ludwig *et al.* [1970], and the subsequent models inferred from this equation [Christensen and Mooney, 1995; Brocher, 2005]. The estimated densities for the sediments are 1.8, 2.0, 2.2, and 2.4 g/cm^3 for the Plio-Pleistocene unit, the thin MSC Upper unit, the thick MSC mobile unit and the pre-MSC unit, respectively. Densities for the upper and lower continental crust, transitional crust, oceanic crust and mantle are 2.8, 2.9, 2.85, 2.9 and 3.3 g/cm^3, respectively. The aim of the models was to optimize the fit between the observed free-air gravity anomalies and the ones calculated from the distribution of densities. The main variables were the nature and thickness of the crust. That allowed us to constrain the width and thickness of the continental, transitional, and oceanic crust along the profiles.

RESULTS

Structure of the southern Balearic margin

We describe the structure of the margin on typical seismic profiles (fig. 3). All the observations from the seismic reflexion profiles have been combined to provide the detailed structural map of the Balearic promontory (fig. 4, C1 and C2). These structural interpretations are presented on a broader map of the depth to basement (fig. 4), integrating the Valencia basin [Maillard *et al.*, 1992, 1999], and the Algerian basin [Mauffret *et al.*, 2004]. The deep structure and the nature of the crust have been constrained by the fit of free-air gravity anomalies on 2D models whose shallow part corresponds to seismic profiles. We used the free-air gravity and the magnetic anomaly maps (fig. 3) to better locate the continent-ocean boundaries and to identify the main structures observed in the oceanic basins. A large part of the West Mediterranean ocean basin is covered by a thick evaporite layer (fig. 1). This layer makes it difficult to identify reflectors beneath the MSC salt where the latter is thick and affected by diapirs. Therefore, the bottom of the continental slope is often hidden, in particular along the steep scarps of Mazarron and Emile Baudot. The southern margin of the Balearic promontory is characterized by large variations of morphology and structure, defining four segments from west to east: the Mazarron escarpment, the South Ibiza margin, the Emile Baudot escarpment, and the South Menorca margin.

Mazarron escarpment

The Mazarron escarpment (ME) is a ~145 km-long, linear, E-W-trending scarp, limiting the deep Algerian basin from the westernmost part of the Balearic promontory (Alicante continental platform). It is marked both by a steep scarp in the bathymetry (1500 m vertical offset on average, fig. 1), and by a rapid deepening of the acoustic basement (fig. 4). It has a maximum height of 2400 m above the surrounding seafloor and a declivity from 14° to 31° [Acosta *et al.*, 2013]. The density of the available seismic lines is irregular in this area. The seismic profile across the ME (fig. 5, Y-Y') shows a 2.3 s TWTT step in the basement (fig. 5, zoom 1). No clear fault is observed, and we infer that the escarpment is the result of a series of faults rather than a single one. A thick layer of MSC evaporites prevents us from following the basement south of the ME in the deep Algerian basin (fig. 5). Rare faults are observed on the promontory north of the scarp, limiting the San Pedro basin or the Torre-Vieja graben (fig. 5). In the San Pedro basin, normal faults offset the acoustic basement and the pre-MSC sediments. The Torre-Vieja graben faults offset the basement and the MSC layers (fig. 5, zoom 2). The faults are difficult to correlate from one profile to another. They appear to have a small lateral extent (fig. 4). We also observe flexures, which affect both the acoustic basement and the sedimentary layers on the promontory (Cogedor high, zoom 2, fig. 5). These folds result from the Pleistocene compression, also marked by anticlines on the Alicante shelf [Cogedor and Tabarca highs, Maillard and Mauffret, 2011; Alfaro *et al.*, 2012]. Small volcanoes are observed on these highs (fig. 4), consistent with those mapped by Acosta *et al.* [2013].

Modeling of the gravity anomalies suggests that the westernmost Balearic promontory consists of a 20-22 km-thick continental crust (fig. 6, A-A'). The thickness of the upper crust appears to decrease from 13 to 10 km from N to S on the promontory. The gravity anomalies are best explained by a southward change to transition crust and a rapid crustal thinning from 18 to 12 km across the Mazarron escarpment. The transition crust rapidly thins oceanward from 12 to nearly 6 km in about 15 km. The Algerian basin is modeled with a 5 to 6 km-thick ocean crust (fig. 6, A-A') consistent with the previous studies [Vidal *et al.*, 1998; Hübscher *et al.*, 2010].

The morphology of the scarp, and the abrupt thinning of the continental crust resulting in a sharp continent-ocean transition, led us to interpret this section of margin as a transform margin.

Southern Ibiza margin

South of Ibiza and Formentera islands, the Ibiza channel is characterized by a series of basins bounded by south-dipping faults, forming tilted blocks getting deeper toward the Algerian basin (fig. 4; fig. 5 Z-Z'). The overall structure of the Ibiza margin displays tilted blocks dipping to the NNW. The acoustic basement displays several steps, about 1 s TWTT each. The two northern basins present sedimentary fans in the pre-MSC unit, which indicate syn-sedimentary, SSE-dipping faults (fig. 5, zoom 3). The northern faults have a larger vertical throw, up to about 2 s TWTT. They affect the Pliocene, but do not reach the most recent sediments. The southern faults have smaller offsets but appear to be currently active. Some chaotic reflectors in the basement might be interpreted as volcanoes.

The gravity modeling across the Ibiza margin (fig. 6, B-B') suggests that the promontory consists of a 10-22 km-thick continental crust, in this area. The top 5 km of the upper crust could be Mesozoic cover, as observed on ESP-7 [Pascal *et al.*, 1992], although the limit of the Mesozoic basin is unclear on the Balearic promontory. The crust reaches its maximum thickness of 22 km in the shallowest part of the promontory, and then progressively thins toward the south to reach 14 km near the Algerian basin. The thickness of the upper crust appears to be nearly constant while the lower crust tends to thin down to 2 km (fig. 6 B-B'). A good fit is obtained with a 7 km-wide zone of 10 km-thick

transition crust between 200 km and 230 km. The Algerian basin displays a 5 to 6 km-thick ocean crust. Our results are consistent with previous studies [Hübscher *et al.*, 2010; Mascle *et al.*, 2012].

Emile Baudot escarpment

The Emile Baudot escarpment (EBE) is a 180 km-long, linear, NW-SE trending segment, eroded by a complex canyon system and intruded by late Pliocene alkaline basalt [Acosta *et al.*, 2001a, 2001b, 2004a, 2004b; Camerlenghi *et al.*, 2009; Lüdmann *et al.*, 2011]. Its height varies from 1400 to 1600 m, and its declivity varies from 3 to 7° in the upper part of the scarp and from 6° to 12° in the lower part of the scarp [Acosta *et al.*, 2001a].

The acoustic basement shows an abrupt deepening toward the Algerian basin near the Central Mallorca depression but is less steep directly south of Mallorca island (fig. 4). West of 3°E, the EBE shows a morphology comparable to that of the Mazarron scarp, with a large step in the acoustic basement (almost 3 s TWTT) but no clearly identified faults (fig. 7 W-W'). The crest of the EBE consists of an acoustic basement ridge, which closes the Central Mallorca depression (fig. 4; fig. 7 W-W'). The entire sedimentary sequence onlaps the ridge, suggesting that the scarp formed in Miocene time (fig. 7, zoom 2). The ridge is

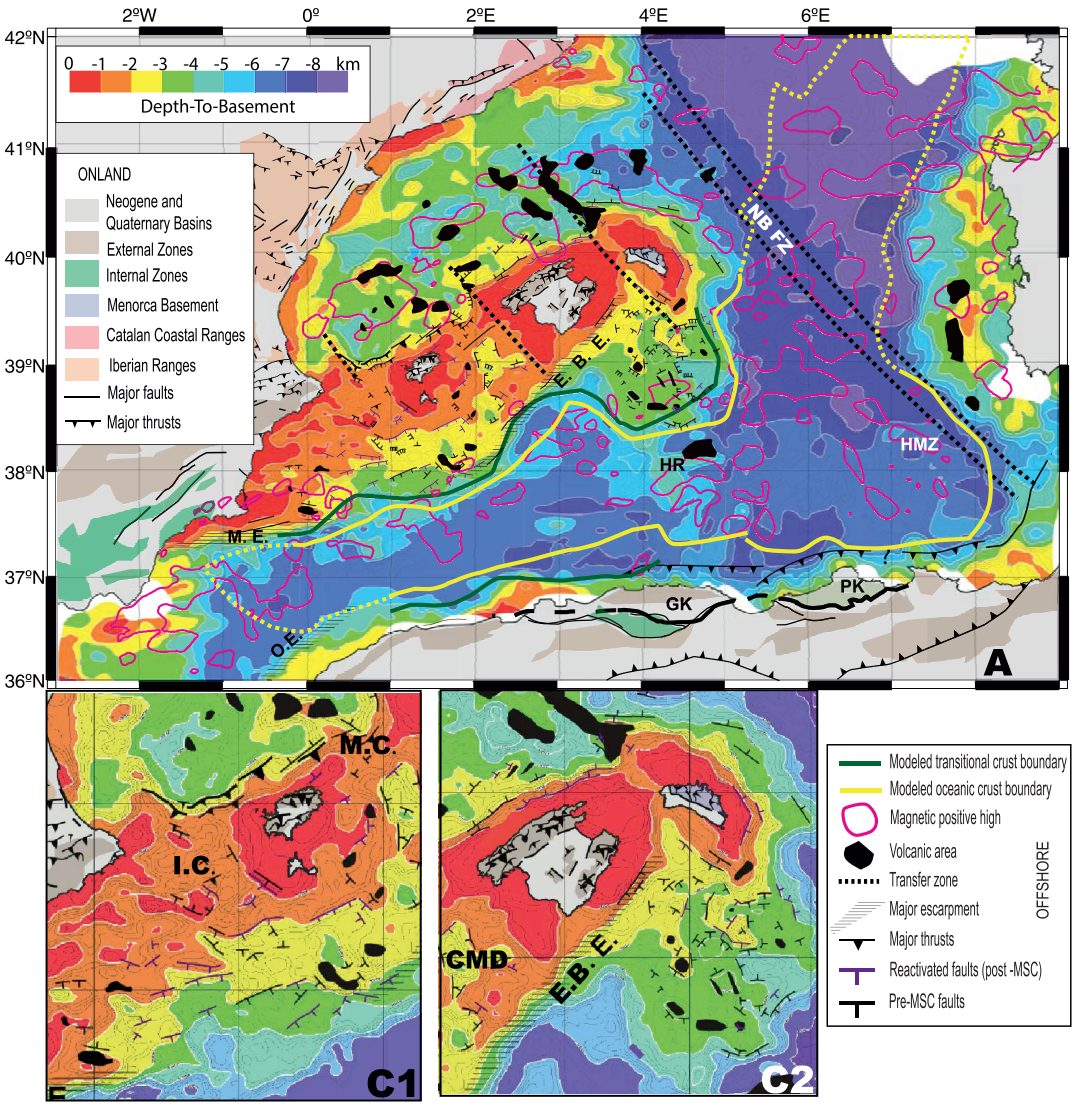

FIG. 4. – Structural map of the western Mediterranean area. A. Depth-to-basement map from the Alboran sea to the Sardinian margin. The basement faults, the depth to basement and the Messinian halite boundary are interpreted from the seismic database presented in figure 3C (B). The thin dashed lines underline the transfer zones from Maillard *et al.* [1992]. The green and yellow lines are continent-transition and transition-ocean crust boundaries, respectively. Pink lines are magnetic anomaly highs (from figure 3). The dashed yellow lines representing the oceanic crust boundary are modified from Medaouri *et al.* [2014] near the Alboran basin and from Gueguen *et al.* [1998], Bache *et al.* [2010] for the Liguro-Provençal basin. The onland geological units are modified from Bartrina *et al.* [1992], Roca and Guimera [1992], Maillard and Mauffret [2013] for the Iberian margin, and from Frizon de Lamotte *et al.* [2008] on the African margin. GK: Grande Kabylie. PK: Petite Kabylie. HR: Hannibal ridge. HMZ: Hamilcar magnetic zone. NBFZ: North Balearic fracture zone. EBE: Emile Baudot escarpment. ME: Mazarron escarpment. OE: Oran escarpment. IC:1048 Ibiza channel. MC: Mallorca channel. CMD: Central Mallorca depression. C1 and C2. Enlargements of A showing the Ibiza channel and Mallorca/Menorca structures. (*Colors refer to PDF version*).

also marked by many volcanic pinnacles (fig. 4 and Acosta *et al*. [2001a]). Widespread volcanic material along the scarp is also suggested by chaotic seismic reflectors and magnetic anomalies, especially near the Emile Baudot seamount (fig. 3 and fig. 7, profile W-W'). The toe of the scarp is concealed by a thick, deformed halite layer in the Algerian basin, preventing us from observing older deformation (fig. 1 and Camerlenghi *et al*. [2009]). Near its crest, north dipping, small-offset normal faults can be observed in the acoustic basement. The eastern part of the EBE offsets the narrow continental platform of the promontory from the western part of the South Menorca block (fig. 7, profile V-V'). Some deep reflections are observed in the acoustic basement of the SMB (fig. 7, zoom 1), which question the nature of this area.

Gravity modeling across the EBE (fig. 6, C-C') is constrained by the observations of deep crustal units on the ESCI profile [Vidal *et al*., 1998] and on the SPIRAL profile [Lepretre, 2012]. As for profile B-B' (fig. 6), a thick Mesozoic cover has been described onshore, but data are too fragmentary to extrapolate it offshore in our model. The Balearic promontory is modeled with continental crust reaching its maximum thickness of 23 km near Mallorca's western cape. From this point to the EBE, the promontory presents a progressive thinning of the crust from 23 to 18 km (fig. 6, C-C'). The thinning appears to occur mostly in the lower crust. The EBE coincides with a drastic shallowing of the Moho from 18 to 12 km depth in less than 30 km. The area is also characterized by a large volcanic area. South of the EBE, the model suggests a 25 km-wide and 12 km-thick transitional crust. The Algerian basin is again modelled with a 5 to 6 km-thick ocean crust.

As for the Mazarron escarpment, from the morphology of the scarp and the juxtaposition of the deep oceanic domain and shallow thick continental crust, we interpret the Emile Baudot escarpment as a transform margin. Both the ME and EBE appear to have recorded a polyphased deformation, including mostly strike-slip motion, and some extension.

South Menorca block

The South Menorca block (SMB) has a NW-SE elongation perpendicular to the general trend of the Balearic promontory. It shows a deeper basement than the Balearic promontory (fig. 4), and a deepening both in the SE and SW

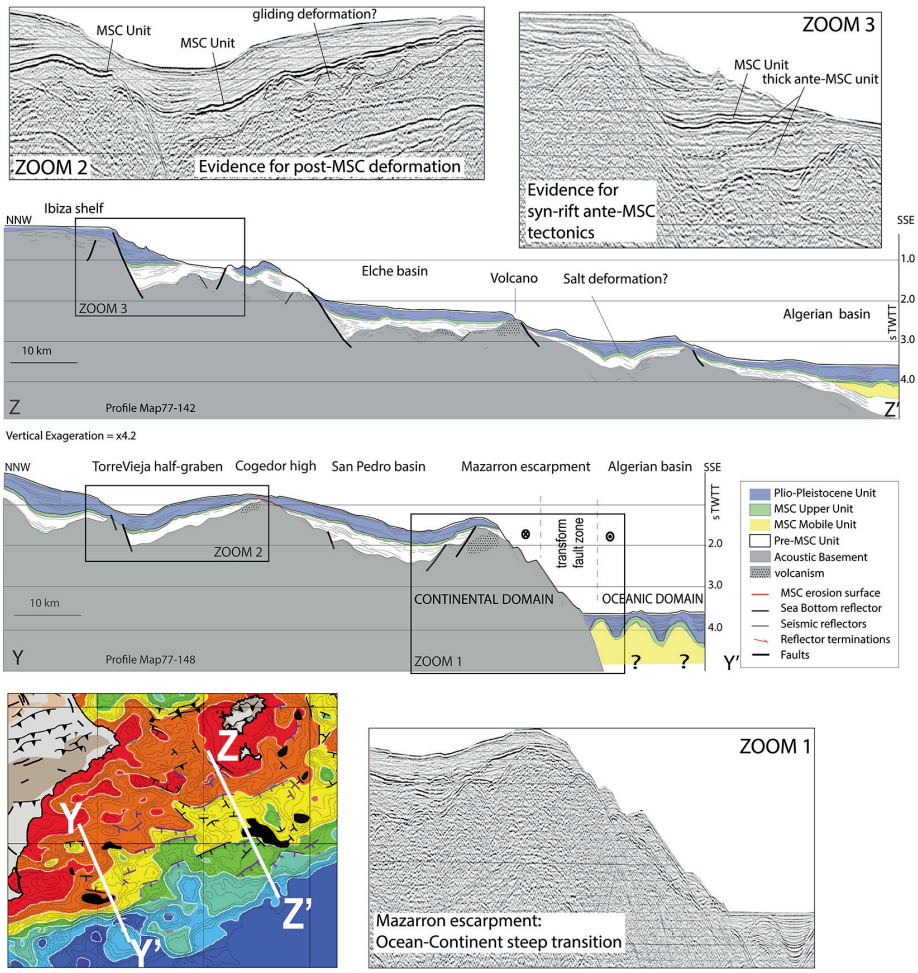

FIG. 5. – Illustrations of the Mazarron escarpment and Ibiza channel. Y-Y': line drawing of the NNW-SSE Map77-148 profile crossing Mazarron escarpment. Z-Z': line drawing of the NNW-SSE Map77-142 profile crossing the Ibiza channel. Vertical exaggeration = 4.2. Location of the profiles and detail of the depth-to-basement map are shown in lower left corner. Zoom 1 shows the seismic expression of the Mazarron escarpment. Zoom 2 displays recent deformation in the Torre-Vieja graben. Zoom 3 illustrates pre-MSC extensional tectonics.

directions. The acoustic basement is very irregular, and appears to have been affected by several phases of extension and by volcanism (fig. 4; fig. 8 U-U' and T-T'). Some of the basement highs characterized by chaotic seismic reflectors are interpreted to be volcanoes (fig. 4). Some of them are associated with magnetic anomalies (fig. 3).

Seismic profiles in perpendicular directions (fig. 8) display normal faults dipping either NE or SW (U-U'), NW or SE (T-T'), limiting small blocks. However, the acoustic basement shows a series of NW-trending highs (fig. 4), which form tilted blocks covered with pre-MSC units and resulting from Miocene or older extension (fig. 8 U-U', zoom 1). The offset of the MSC unit might be due to the paleotopography inherited from the rifting stage. However, the MSC and Plio-Pleistocene units are clearly tilted, showing a recent (at least post MSC) reactivation of some of the faults (fig. 8, both profiles), as observed in the south Ibiza margin segment. Bending and, in some parts, erosion of the MSC unit suggest a recent uplift (fig. 5, zoom 1 and fig. 8, zoom 2).

The gravity model shows a 14 km-thick continental crust at the southern tip of the SMB, with 6 km of upper crust and 8 km of lower crust (fig. 9, D-D'). The crust thins progressively to 8 km to the south of the profile, with preferential thinning in the lower crust. South of the SMB, the gravity fit suggests a 7 to 8 km-thick transitional crust with a width comparable to that observed on sections AA' and BB' (fig. 6) to the west. The Algerian basin section of the profile shows a 100 km-wide basin, floored by a 5 to 6 km-thick oceanic crust. A gravity anomaly low near the center of the oceanic basin is best explained by a thickening of the oceanic crust to 7 km, which is correlated with a structural high (fig. 4). The gravity model along a section parallel to the EBE shows a 20 km-thick continental crust close to the Menorca shelf (fig. 9 E-E'), which progressively thins southwestward to 14 km. Thinning appears to be more important in the upper than lower crust. In the southern 90 km of the profile, the fit of the gravity anomaly is obtained with a 12 to 8 km-thick transitional crust. Another profile parallel to the EBE farther south (fig. 9, F-F') shows that both the Provençal and the Algerian basins are modeled with a 5 to 6 km-thick oceanic crust. The model also suggests the presence of a narrower transition crust west of the SMB compared to the eastern transition with the Liguro-Provençal basin (fig. 9, F-F'). The SMB is modeled with a double layered continental crust with an average thickness of 13 km. The crustal thinning seems to be more important toward the Liguro-Provençal basin than toward the Algerian basin, but the transitional crust zone is narrower to the west (fig. 9, F-F').

Structure of the southwestern Mediterranean oceanic basins

The combined aeromagnetic surveys [Galdeano *et al.,* 1974; Galdeano and Rossignol, 1977] provide an almost complete, high-resolution magnetic coverage of the West Mediterranean region (fig. 3). Two areas, which were not covered by the original aeromagnetic surveys, have been interpolated from scarcer data points and should be interpreted with caution (light color areas in figure 3). The free-air gravity anomaly map (fig. 3) also displays a complete coverage since it has been derived from satellite altimetry over the oceans.

The magnetic and gravity anomaly maps show a great complexity of the western Mediterranean sea, in particular southwest of the Liguro-Provençal basin. The North Balearic fracture zone (NBFZ) marking the western limit of the Liguro-Provençal basin is clearly observed in the magnetic and gravity maps (fig. 3) and with a clear deepening of the

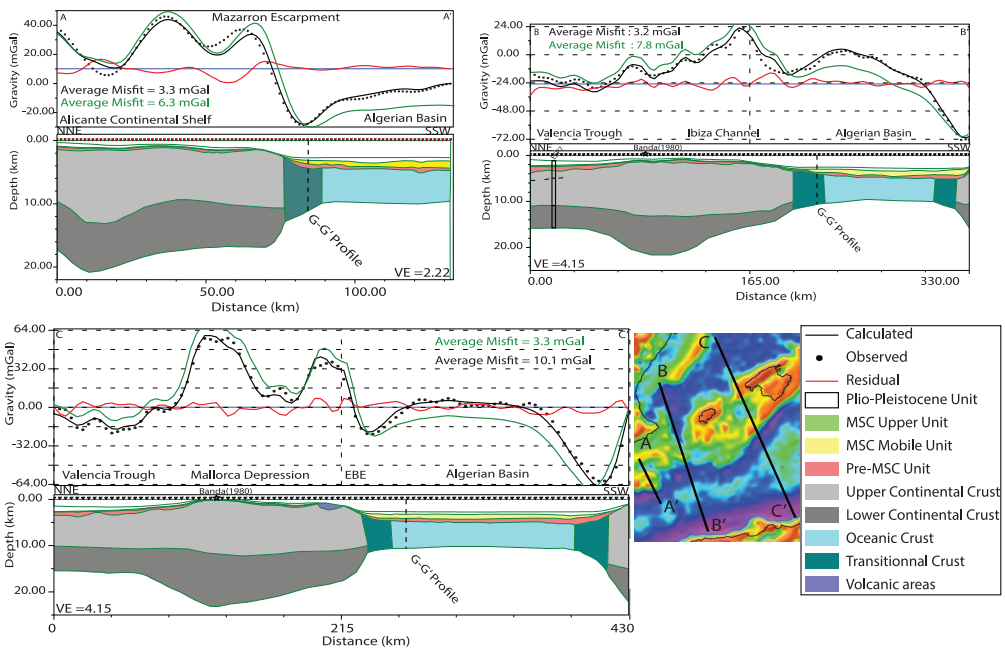

FIG. 6. – Gravity models along seismic profiles located on free-air gravity anomaly map.
A-A': model along Map77-148 profile across the Mazzaron scarp. B-B': model along Ray23, Meds77-30 and Sonatrach77-15 profiles across the Ibiza channel. C-C': model along Valsis805, Map77-132, Meds26 and Sonatrach77-20 profiles across the Mallorca Central depression and the Emile Baudot escarpment. Green line: model considering continental crust in the Algerian basin, showing a larger misfit. (*Color refers to PDF version*).

basement (fig. 4). The volcanic areas in the Valencia trough and the South Menorca area are marked by high-amplitude magnetic highs and lows. This confirms the interpretation of some of the basement highs in terms of volcanoes (fig. 4, Acosta *et al*. [2001a, 2002]). The continent-ocean boundary (COB) is usually well marked by a low in the free-air gravity anomaly associated with a step in the basement depth (fig. 8 to 10), allowing to define the COB between modeled gravity profiles. The north Algerian COB is marked by a magnetic high.

The Algerian basin area can be divided into three regions showing different types of magnetic patterns (fig. 3). To the east between 5°E and 8°E, a domain with a general triangular shape displays the most prominent magnetic lineations of all the western Mediterranean. It is located just west of the NBZF, in the area presented as a transition zone between the Liguro-Provencal and the Algerian basins in many geodynamic models (fig. 2). The northern point of the triangle is located near 40°N, 5°E. The gravity anomaly map shows gravity highs forming a V-shape pointing to the same point to the NW (fig. 3), outlining the triangle, associated with highs in the magnetic anomalies, trending N120°E to the east ("Hamilcar" magnetic anomaly of Mauffret *et al*. [2004], HMA on figure 3), and N-S to the west (fig. 3 and fig. 11). Within the V shape, a series of magnetic anomalies are observed, trending N130°E to N145°E [e.g., Bayer *et al*., 1973; Schettino and Turco, 2006]. The basement depth within the triangle is about 6000 m on average, with a deepening to ~7000 m in the north and in the south (fig. 4). These depths are similar to those of the western part of the Algerian basin, and shallower than those of the Liguro-

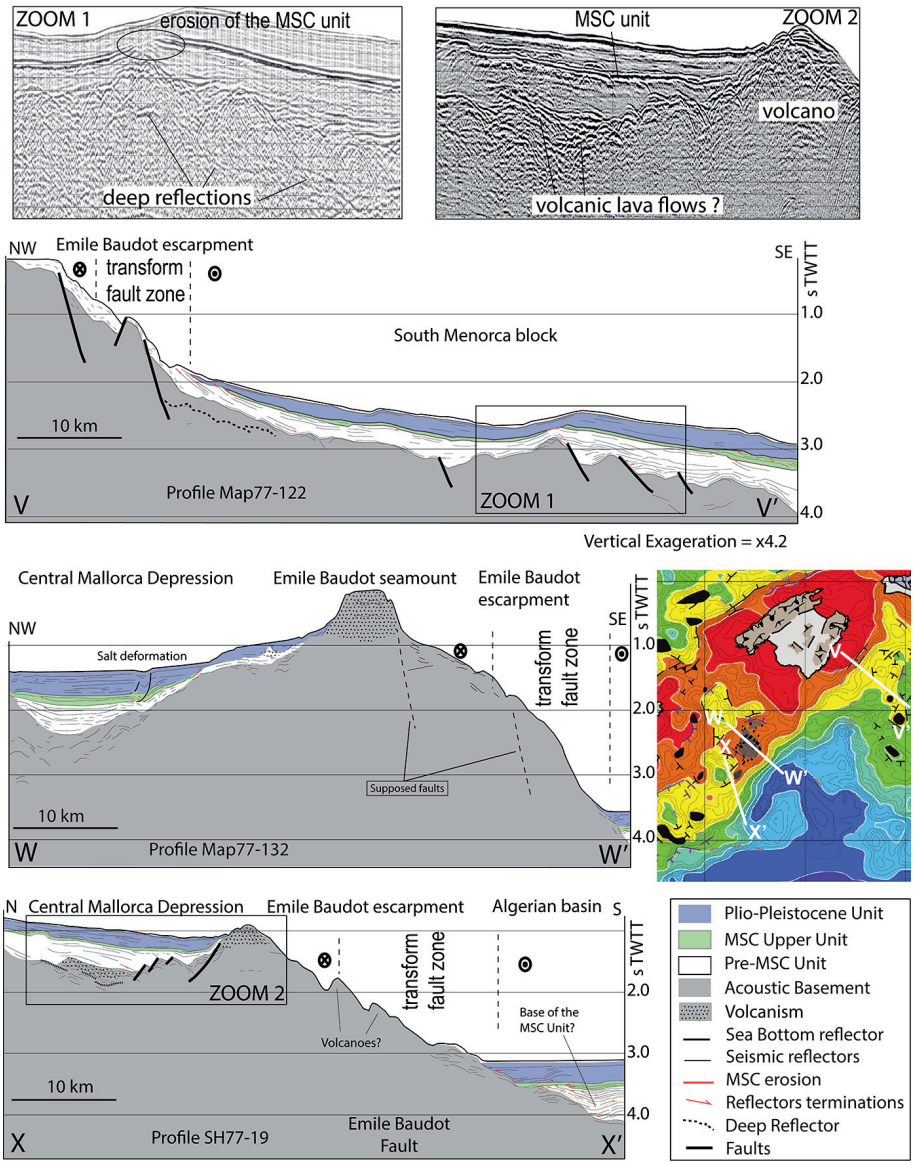

FIG. 7. – Illustrations of the lateral evolution of the Emile Baudot escarpment (EBE). X-X': line drawing of the N-S Sonatrach77-19 profile crossing the western end of the EBE. W-W': line drawing of the NW-SE Map77-132 profile crossing the center of the EBE. V-V': line drawing of the NW-SE Map77-122 profile crossing the eastern end of the EBE. Vertical exaggeration = 4.2. Location of the profiles and detail of the depth-to-basement map are shown in right corner. Zoom 1 illustrates the recent reactivation on the South Minorca block (SMB). Zoom 2 shows the closure of the southern part of the Central Mallorca depression (CMD) on the EBE.

Provençal basin (>8000 m, fig. 4). The eastern side of the V coincides with the southern prolongation of the NBFZ. The northwestern edge of the V partly bounds the South Menorca block. Within this domain, the lineations are best defined in the center of the triangle, defining several corridors (eastern Algerian corridors, EAC, and fig. 11). The pattern of magnetic lineations implies that this region results from an oceanic opening in the NE-SW direction (fig. 11).

The second domain is observed between the SMB and the Algerian COB between 2°E and 5°E (fig. 3 and fig. 10). It confirms the presence of a narrow oceanic domain south of the SMB. This region is characterized by a more chaotic pattern in the magnetic anomalies, irregular gravity anomalies, and a basement depth 1000 to 2000 m shallower than the surroundings (fig. 3, 4 and 10), the "Hannibal ridge" [Mauffret *et al.*, 2004]. The boundaries of the domain are not clearly observable on the gravity grid, which only shows a general NW-SE trending gravity low (fig. 3). Short magnetic lineations display directions from NE-SW just south of the SMB to NNE-SSW near the Algerian margin (fig. 3). The ocean crust in the corner formed by the EBE and the SMB is marked by magnetic and gravity anomalies with no clear trend (fig. 3 and 10). The general orientation of the magnetic lineations in this domain suggests a NNW-SSE opening. The observed shallow basement and the crustal structure obtained by gravity modeling along profile D-D' suggest a thicker oceanic crust in this domain compared to the surrounding regions.

The third magnetic region extends between 4°W and 2°E in the rest of the Algerian basin (fig. 3). In this region, the magnetic anomalies are relatively isolated, but clearly define a corridor trending NE-SW, parallel to the EBE. High-amplitude positive anomalies near 1°E and 0° have a NW-SE trend, perpendicular to the corridor. The pattern of the observed lineations suggests that this part of the Algerian basin was created by spreading in a NE-SW direction, along short ridge segments. Such short segments separated by large transform faults have been inferred in the Alboran sea from a seismic and magnetic survey offshore Algeria [Medaouri *et al.*, 2014]. For all magnetic anomalies observed in the western Mediterranean basin, profiles across magnetic lineations are too short to be compared to synthetic models.

DISCUSSION

Segmentation and kinematics of the South Balearic margin

The South Balearic margin displays large variations in structure and deformation (fig. 4), so that it can be divided into four different segments. The morphology and crustal structure of the ME and EBE, showing a sharp transition between continental and oceanic domains, are similar to those of well-studied transform margins, such as the Côte d'Ivoire-Ghana margin [Sage *et al.*, 1997; Basile *et al.*, 1993, 1998, 2013] or the Grand Bank margin [Keen *et al.*, 1990]. Moreover, the top of the EBE could be interpreted in terms of "marginal ridge", also characteristic of transform margins, but the abundance of volcanic constructions along the scarp prevents us from describing its structure more precisely [Acosta *et al.*, 2001a]. These two segments of the South Balearic margin can therefore be interpreted to be segments of transform margin, implying a significant strike-slip motion. A strike-slip motion along the EBE has been inferred in previous works [Lonergan and White, 1997; Acosta *et al.*, 2001; Mauffret *et al.*, 2004]. The relationships between the trend of the EBE and the NW-SE trending tilted blocks and normal faults on the western side

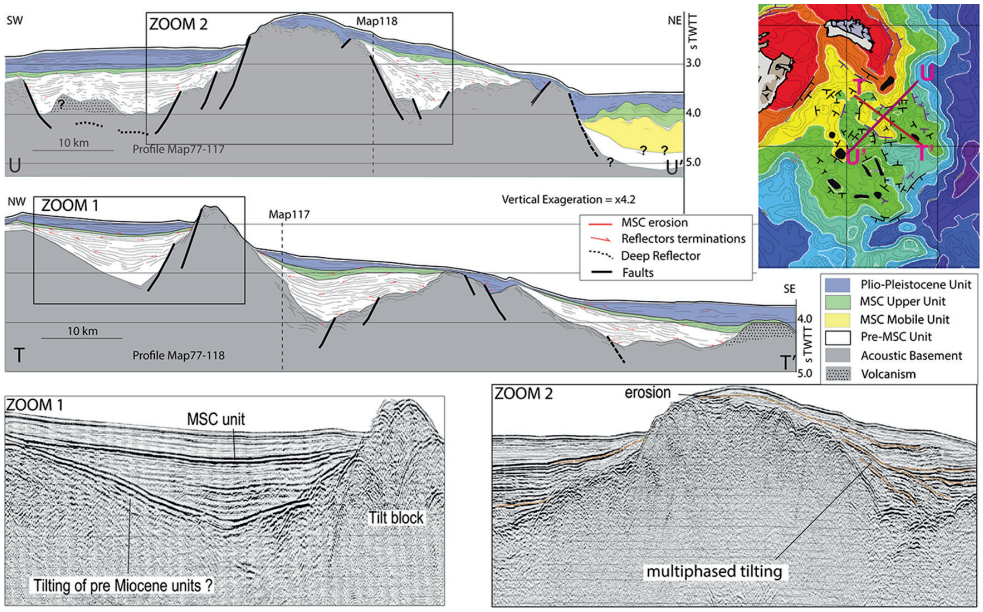

FIG. 8. – Illustrations of the South Menorca block (SMB). U-U': line drawing of the NE-SW Map77-117 profile crossing the South Menorca block. T-T': line drawing of the NW-SE Map77-118 profile crossing the South Menorca block. Vertical exaggeration = 4.2. Position of the profiles and detail of the depth-to-basement map are on the upper right corner. Zooms 1 and 2 illustrate local tilted blocks. Zoom 1 shows a clear pre-MSC activity which might be as old as Oligo-Miocene. Zoom 2 displays important Plio-Pleistocene tilting.

of the SMB imply a dextral motion along the transform margin (fig. 4, also Acosta *et al.* [2001a]). A similar NW-SE trend is observed at the eastern tip of the Mazarron escarpment, but the relation between the south Ibiza margin and the Mazarron escarpment points to a more complex and probably multiphase history (fig. 4).

The other margin segments, the south Ibiza margin and the South Menorca block, are marked by a smoother bathymetry, a gentler deepening of the acoustic basement, and a more gradual thinning of the continental crust. The transition between the continental and oceanic domains is progressive. These features suggest that these segments are mostly divergent margin segments. Three types of processes, however, make the structure and kinematics along these segments more difficult to assess. First, they are affected by Miocene to recent volcanism (fig. 1 and fig. 4, see also Acosta *et al.* [2002]). Second, they show evidence for recent deformation. Some of the basement faults affect the whole sedimentary cover, which shows that the region has been reactivated recently (fig. 4, also Acosta *et al.* [2001a, 2001b, 2013]; Alfaro *et al.* [2012]; Maillard and Mauffret [2013]). Finally, these margin segments appear to have been affected by different tectonic events. The south Ibiza margin displays tilted blocks, mostly oriented E-W, and S to SE dipping faults, with no evidence for strike-slip motion (fig. 4). The South Menorca block is marked by different styles of deformation on either side of the bathymetry high. On its western side, the normal faults preferentially trend NW-SE, and dip SW, whereas on the eastern side, the preferential orientation is NE-SW, with a SE dip (fig. 4). The variety of fault directions clearly suggests that the SMB has undergone different tectonic phases. The South Balearic margin from the ME to the EBE has therefore seen a transform motion in a large part of its history, but some segments of the margin have also clearly been shaped by extensional deformation. The segmentation of the margin may also reflect variations in the inherited structure of the margin, or differences in rheological properties of the continental margin. Further studies are required to understand the contrast in structure along the South Balearic margin. In the following, we focus on the implications of the transform margin motion on the kinematics of the Algerian basin.

Geodynamic implications for the western Algerian basin

Our results provide insights into the kinematics of the south Balearic margin and the Algerian oceanic basin, from which we can discuss the different geodynamic models for the opening of the Algerian basin. In the models with a N-S opening of the Algerian basin, the South Balearic margin would act as a divergent margin, while the NBFZ will act as a transform margin in the north next to the Valencia trough, and as an oceanic transform fault to the south. These models are in agreement with a southward migration of the Kabylies, but do not explain a westward drift of the Alboran block or a transform motion along segments of the south Balearic margin. In the models with an E-W or NE-SW opening of the Algerian basin, the entire southern Balearic margin would be a transform margin. This type of model would account for a westward drift of the Alboran domain but is not compatible with a southward motion of the Kabylies. Moreover, the different accretion directions between the Algerian and Liguro-Provençal basins imply a complex transition zone in the southern part of the NBFZ [Rehault *et al.*, 1984].

The observations on the crustal structure and deformation of the South Balearic margin imply that the margin acted as a significant right-lateral transform margin. This kinematic constraint favors models where the Algerian

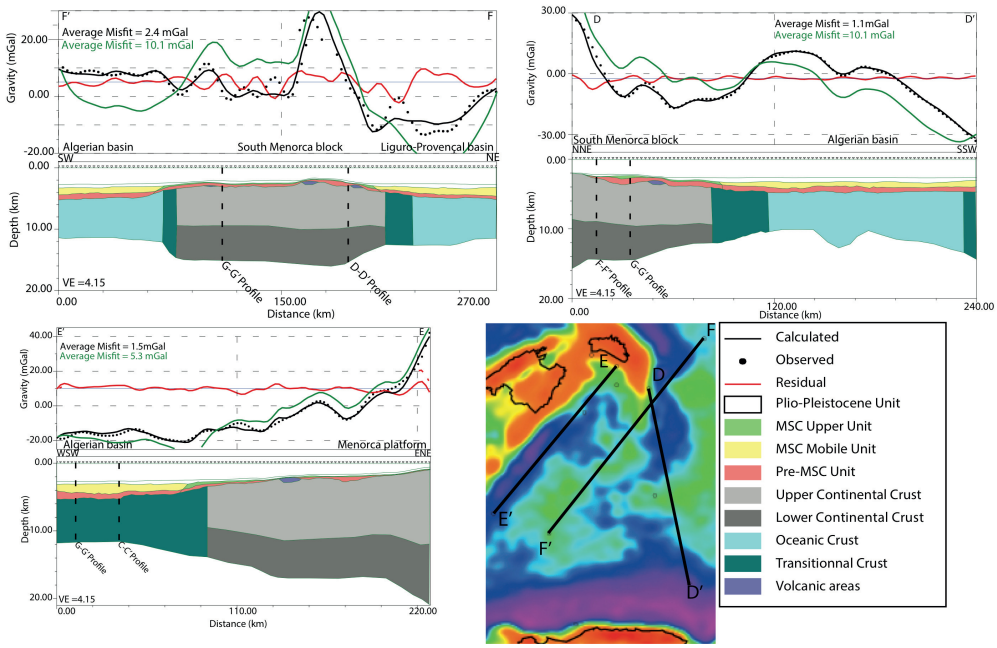

FIG. 9. – Gravity models along seismic profiles located on free-air gravity anomaly map. D-D': model along Sonatrach77-23 profile across the South Menorca block. E-E': model along Map77-109 profile across the South Menorca block. F-F': ENE model along Sonatrach77-22 and 23 profiles across the South Menorca block. Green line: model considering continental crust in the Algerian basin, showing a larger misfit. (*Color refers to PDF version*).

basin opened in a general NE-SW direction. South of the margin, the magnetic and gravity anomaly maps show clear lineations in the Algerian basin, which define corridors trending E-W to NE-SW (fig. 11). Unlike what is observed in most ocean basins, however, a relict spreading center is not identifiable in the western Mediterranean. This alone suggests that, even though they were short lived, the mid ocean ridges which created seafloor in this area are likely to have had intermediate to fast spreading rates. Despite the lack of clear relict axis, the corridor of ocean lithosphere is relatively well defined by short but linear magnetic anomalies perpendicular to the EBE (fig. 11). The corner of the EBE and the SMB forms the northeastern boundary of the corridor. Its southern boundary is outlined by an elongated positive magnetic anomaly. To the southwest, the corridor is limited by a linear segment of the COB along the northwest Algerian margin, the Oran escarpment (OE, fig. 4). This part of the COB shows evidence for current deformation [Domzig *et al.*, 2006]. The current compressive deformation along the northwestern margin of Algeria likely disrupts the former transform margin (fig. 11) [Deverchère *et al.*, 2005; Domzig *et al.*, 2006].

The northwestern boundary of the oceanic corridor described above is complex. It likely largely follows the transform scarps of the South Balearic margin, but also follows the south Ibiza margin in between (fig. 11). It is possible that the motion along the Mazarron escarpment has been partly transtensive. To the NE, the corridor extends along EBE up to the SMB. The NW-SE trending tilted blocks limiting the SMB form a divergent segment at the tip of the EBE transform segment. The corridor is closed to the east by a group of chaotic magnetic anomalies which does not seem to have any equivalent to the west.

Spreading in the corridor defined south of the EBE implies a 400 km westward drift of a domain about 80 km wide creating the western Algerian basin. Figure 11a shows the reconstruction of the area near 19 Ma, after closing the western Algerian basin using the western Algerian corridor (WAC, fig. 11b). Such kinematics are consistent with models describing the westward motion of the Alboran area along two subduction-transform edge propagator (STEP) faults [Govers and Wortel, 2005], driven by the rollback of the Gibraltar slab subduction zone [Royden, 1993; Lonergan and White, 1997; Mauffret *et al.*, 2004; Gutscher *et al.*, 2002, 2012; Bezada *et al.*, 2013; Medaouri *et al.*, 2014; Van Hinsbergen *et al.*, 2014]. Our interpretation provides a minimum value for the motion of the Alboran domain related to its drift and seafloor spreading, which should be added to the displacement related to the continental rifting. The total amount of 500-600 km is compatible with previous estimates, and with the 800 km length of the Gibraltar subducted slab observed in tomographic images [see Van Hinsbergen *et al.*, 2014 and references herein].

Geodynamics of the eastern Algerian basin and the Kabylies

Our observations also point to a NE-SW oceanic opening of the eastern Algerian basin, implied by the clear NW-SE orientation of the magnetic lineations (fig. 11). Such an opening for the eastern Algerian basin is actually difficult to reconstruct in detail if one assumes that the Kabylies were part of the African plate before the opening of the Algerian basin. Many observations are better accounted for by the opening of the eastern Algerian basin coeval with a southwestward drift of the Kabylies. We therefore suggest a scenario where this oceanic spreading episode was accompanied by a southwestward motion of the Kabylies, in two

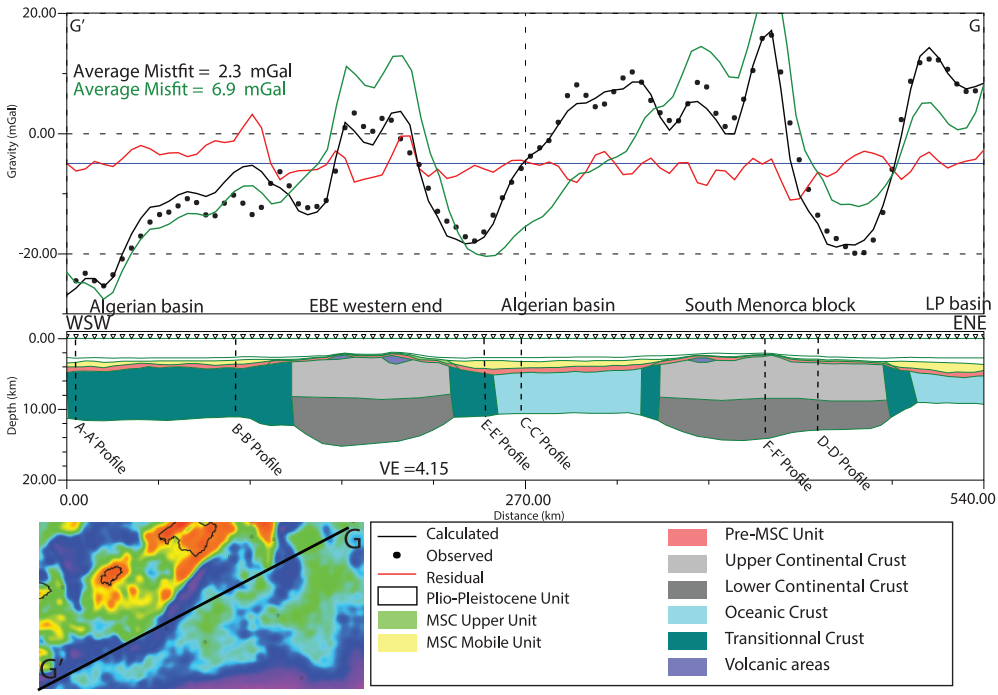

FIG. 10. – Gravity models along seismic profiles located on free-air gravity anomaly map. G-G': model along Sonatrach77-36 profile across the Algerian basin. Green line: model considering continental crust in the Algerian basin, showing a larger misfit. (*Color refers to PDF version*).

corridors (eastern Algerian corridor, EAC, fig. 11b) subparallel to the western Algerian corridor, driven by the rollback of the Tethysian subduction (fig. 11).

Other observations support this scenario. In particular, tomographic sections across North Africa and the Algerian basin presented in Spakman and Wortel [2004] and van Hinsbergen *et al.* [2014] clearly show faster velocity anomalies suggesting the presence of a slab dipping to the east under the Petite Kabylie (fig. 11b). Unlike all previous models, we suggest that the rollback of the Maghrebian slab north of Africa did not occur only toward the south, but partly to the west, like the Gibraltar slab, implying the formation of several STEP [Govers and Wortel, 2005] configurations along the north Algerian margin (fig. 11). This subduction pattern implies that the main Tethysian slab was torn into several pieces, one going to the east and forming the Tyrrhenian sea, and one going to the west and forming the entire Algerian basin, this part itself torn into the Gibraltar slab and one or two Kabylies slabs (east Algerian slab in Wortel and Spakman [2004]. The tomographic images support this pattern. This geometry of the slab and the identification of Grande Kabylie and Petite Kabylie domains are also supported by the distribution of the seismicity. Maps of earthquake epicenters show more numerous epicenters around and between the Kabylies than elsewhere in eastern Algeria [Boughacha *et al.*, 2004; Yelles-Chaouche *et al.*, 2006; Serpelloni *et al.*, 2007]. Some earthquake hypocenters are relatively deep, possibly related to slab deformation. Further investigations about the depth and kinematics of earthquakes around the Kabylies would allow testing our scenario.

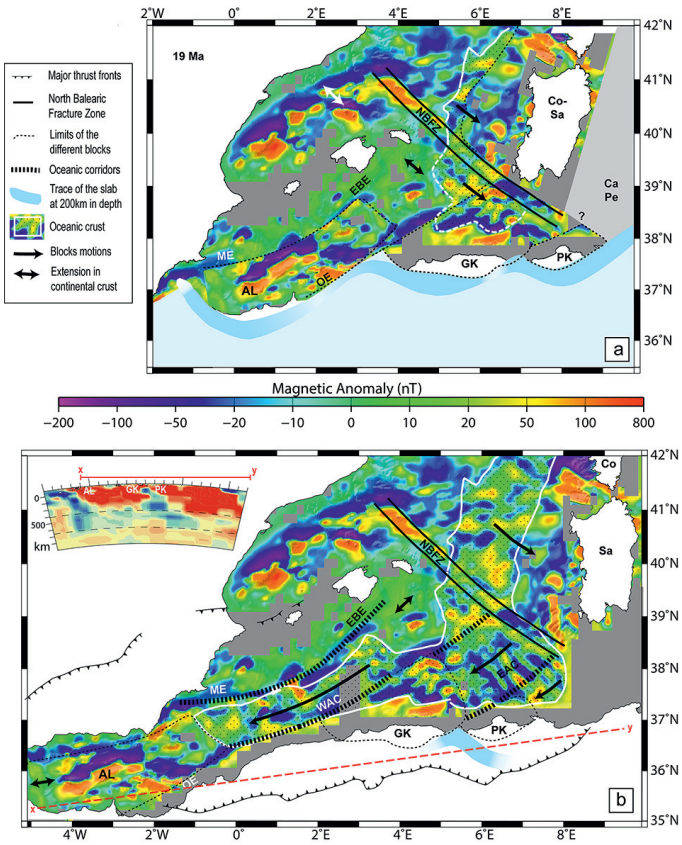

FIG. 11. – Kinematic reconstructions depicting the main features of the proposed geodynamic model, shown on the magnetic anomaly map. White lines are limits of the oceanic crust (from figure 3). NBFZ: North Balearic fracture zone, GK: Grande Kabylie. PK: Petite Kabylie, ME: Mazarron escarpment, EBE: Emile Baudot escarpment, OE: Oran escarpment, AL: Alboran domain, Co: Corsica, Sa: Sardinia, Ca: Calabria, Pe: Peloritani. EAC: eastern Algerian corridors, WAC: western Algerian corridor. A. Reconstruction of western Mediterranean area before the main opening of the Algerian basin, at around 19 Ma, during the opening of the Liguro-Provençal basin. Oceanic opening occurs in a SSE-NNW direction parallel to the NBFZ. A small oceanic domain was probably forming just south of the NBFZ during a first southward motion of the GK. B. Present-day situation, after opening of the Algerian basin in a ENE-WSW direction in two main corridors. Upper left corner shows seismic tomography section across northern Africa marked by thin black line [from Spakman and Wortel, 2004].

The last stage of deformation in the Kabylies is dated around 16 Ma, which constrains the opening of the eastern Algerian basin between about 19 and 16 Ma. That would be partly coeval to the end of the Liguro-Provençal spreading, and possibly to the western Algerian basin. Such a scenario implies a similar direction for the motion of the Alboran domain and the Kabylies. The amount of drift is larger for the Alboran domain than for the Kabylies (about 400 km vs 200 km of oceanic accretion, respectively). The pattern of magnetic anomalies in the west and east Algerian basins is different (fig. 3 and fig. 11), suggesting different ages or spreading rates for the two oceanic floor areas. Because of the lack of identification of magnetic anomalies, the timing of the oceanic spreading in the Algerian basin is unknown, and could only be determined by drilling of oceanic floor beneath the salt and sediment. We infer that NE-SW ocean spreading in the Algerian basin started some time near or after 19 Ma, and we have tentatively drawn a reconstruction of the basin near that time (fig. 11a). This reconstruction shows that some ocean crust formed in the Algerian basin during the opening of the Liguro-Provençal basin (fig. 11a), with the NBFZ as a transform boundary between the two domains, before the opening of the two corridors of the Algerian basin. These areas likely resulted from an episode of NW-SE extension and spreading associated with the opening of the Liguro-Provençal basin. This episode is clearly suggested by the E-W to NE-SW normal faults and structure over the Ibiza margin and the SMB. This episode of extension is probably linked to the Valencia trough rifting along NW-SE transfer faults parallel to the NBFZ, which segment the Balearic promontory (fig. 4) [Maillard *et al.*, 1992]. These NW-SE transfer faults are still observable within NW-SE basement steps along Mallorca and Menorca but they are overprinted by the EBE (fig. 4), which tends to confirm the suggested chronology of the different phases. The succession of both extensional phases in different directions results in the complex pattern of the deformation of the SMB (fig. 4). However, the south Ibiza margin records only the NW-SE one and is not overprinted by the strike-slip motion, which could show that the EBE and the ME have been active successively.

CONCLUSION

We studied the structure of the southern Balearic margin to understand the kinematics of the adjacent basins. To this end, we interpreted a large database of seismic profiles and tested hypothesized interpretations for the margin by

creating gravity models across the Balearic margin and the southern basins.

We show that four different segments may be distinguished along the south Balearic margin based on the morphology and structure of the margin. Two segments, the Mazarron and Emile Baudot escarpments, show steep scarps, a rapid deepening of the basement and thinning of the continental crust. The two other segments are marked by a smoother bathymetry, and a gentler deepening of the basement and thinning of the continental crust. We interpret the two steep segments as transform margin segments, implying a strike-slip motion. The two other segments are interpreted in terms of divergent margins affected by different episodes of extension and transform motion, and by recent tectonics and volcanism.

The transform motion inferred along the south Balearic margin supports models in which the Alboran domain migrates to the west or southwest with respect to Eurasia. The kinematics of the Alboran domain and the magnetic lineations in the eastern Algerian basin lead us to suggest a new scenario for the opening of the east Algerian basin. In our scenario, the Algerian basin opened shortly in a NW-SE direction, creating some seafloor just south of the North Balearic fracture zone, before a general opening in the NE-SW direction. This NE-SW oceanic spreading episode was accompanied by a southwestward motion of the Kabylies, in two corridors sub-parallel to the Alboran corridor, driven by the rollback of the Tethysian subduction to the west. The suggested motion of the Kabylies is supported by the image of a slab in the seismic tomography images, and by the distribution of earthquakes in northeastern Algeria. The different episodes of extension are recorded in some segments of the South Balearic margin.

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