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Detailed tectonic reconstructions of the Western Mediterranean region for the last 35 Ma, insights on driving mechanisms

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Abstract – Slab retreat, slab tearing and interactions of slabs are first-order drivers of the deformation of the overriding lithosphere. An independent description of the tectonic evolution of the back-arc and peripheral regions is a pre-requisite to test the proposed conceptual, analogue and numerical models of these complex dynamics in 3-D. We propose here a new series of detailed kinematics and tectonic reconstructions from 35 Ma to the Present shedding light on the driving mechanisms of back-arc rifting in the Mediterranean where several back-arc basins all started to form in the Oligocene. The step-by-step backward reconstructions lead to an initial situation 35 Ma ago with two subduction zones with opposite direction, below the AlKaPeCa block (i.e. belonging to the Alboran, Kabylies, Peloritani, Calabrian internal zones). Extension directions are quite variable and extension rates in these basins are high compared to the Africa-Eurasia convergence velocity. The highest rates are found in the Western Mediterranean, the Liguro-Provençal, Alboran and Tyrrenhian basins. These reconstructions are based on shortening rates in the peripheral mountain belts, extension rates in the basins, paleomagnetic rotations, pressure-temperature-time paths of metamorphic complexes within the internal zones of orogens, and kinematics of the large bounding plates. Results allow visualizing the interactions between the Alps, Apennines, Pyrenean-Cantabrian belt, Betic Cordillera and Rif, as well as back-arc basins. These back-arc basins formed at the emplacement of mountain belts with superimposed volcanic arcs, thus with thick, hot and weak crusts explaining the formation of metamorphic core complexes and the exhumation of large portions of lower crustal domains during rifting. They emphasize the role of transfer faults zones accommodating differential rates of retreat above slab tears and their relations with magmatism. Several transfer zones are identified, separating four different kinematic domains, the largest one being the Catalan-Balearic-Sicily Transfer Zone. Their integration in the wider Mediterranean realm and a comparison of motion paths calculated in several kinematic frameworks with mantle fabric shows that fast slab retreat was the main driver of back-arc extension in this region and that large-scale convection was a subsidiary driver for the pre-8 Ma period, though it became dominant afterward. Slab retreat and back-arc extension was mostly NW-SE until ~ 20 Ma and the docking of the AlKaPeCa continental blocks along the northern margin of Africa induced a slab detachment that propagated eastward and westward, thus inducing a change in the direction of extension from NW-SE to E-W. Fast slab retreat between 32 and 8 Ma and induced asthenospheric flow have prevented the transmission of the horizontal compression due to Africa-Eurasia convergence from Africa to Eurasia and favored instead upper-plate extension driven by slab retreat. Once slab retreat had slowed down in the Late Miocene, this N-S compression was felt and recorded again from the High Atlas to the Paris Basin.

Keywords: Western Mediterranean / plate reconstructions / slab retreat / transfer zones / exhumation / weak crust

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Résumé – Reconstructions détaillées de la Méditerranée occidentale depuis 35 Ma, implications en terme de mécanismes moteur. Le retrait des panneaux plongeants dans les zones de subduction, leurs éventuelles déchirures et les interactions entre ces panneaux sont des moteurs de premier ordre de la déformation lithosphérique. Une description indépendante de l’évolution tectonique des régions arrière-arc et de leur périphérie est un prérequis indispensable pour tester les différents modèles conceptuels, analogiques ou numériques de ces interactions complexes en 3-D. Nous proposons une série de nouvelles reconstructions cinétiques et tectoniques de la Méditerranée occidentale depuis 35 Ma qui éclairent les mécanismes moteurs de l’extension arrière-arc. La Méditerranée est caractérisée par plusieurs domaines arrière-arc qui ont tous commencé à se former pendant l’Oligocène inférieur. La reconstruction pas-à-pas en remontant le temps conduit à une situation où deux zones de subduction à vergence opposées sont actives sous le bloc AlKaPeCa. Les directions d’extension sont variables selon les bassins et les taux d’extension sont élevés par rapport à ceux de la convergence Afrique-Eurasie. Les taux les plus élevés sont observés en Méditerranée occidentale dans le Bassin Liguro-Provençal, la Mer d’Alboran et la Mer Tyrrhénienne. Nos reconstructions sont basées sur les taux de raccourcissement dans les chaînes de montagnes qui entourent ces bassins, les taux d’extension dans les bassins, les rotations paléomagnétiques, les chemins pression-température-temps des complexes métamorphiques dans les zones internes des orogènes et la cinématique des grandes plaques alentour. Les résultats permettent de visualiser les interactions entre les Alpes, les Pyrénées, les Apennins, les Cordillères Bétiques et le Rif, et les bassins arrière-arc. Ces derniers se forment à l’emplacement des chaînes de montagnes éocènes auxquelles sont superposées des arcs volcaniques et donc dans des domaines de croûte chaude et épaisse expliquant la genèse de *metamorphic core complexes* et l’exhumation de larges portions de croûte inférieure pendant le rifting. Les reconstructions montrent l’importance des zones de transfert au-dessus des déchirures des panneaux plongeants et leurs relations avec les arcs magmatiques. Plusieurs zones de transfert sont identifiées, la plus importante étant la zone de transfert Catalogne-Baléares-Sicile. L’intégration de ces reconstructions dans le cadre plus large de la Méditerranée et une comparaison des chemins cinématiques calculés dans des repères cinématiques différents montrent que le retrait des panneaux plongeants est le moteur principal de la déformation arrière-arc et que la convection à grande échelle et la convergence Afrique-Eurasie sont des facteurs de deuxième ordre pour la période antérieure à 8 Ma et qu’elles redeviennent primordiales ensuite. Le retrait des panneaux plongeants est essentiellement N-S ou NW-SE jusqu’à environ 20 Ma, moment où se produisit l’accostage des blocs du domaine AlKaPeCa sur la marge nord-africaine, induisant une déchirure qui se propage ensuite vers l’ouest et vers l’est et un changement de la direction d’extension de N-S à E-W. Le retrait des panneaux plongeants entre 32 et 8 Ma a empêché la transmission des contraintes horizontales dues à la convergence Afrique-Eurasie et favorisé au contraire l’extension arrière-arc. Quand ce retrait ralentit au cours du Miocène supérieur à l’ouest, la compression N-S est à nouveau enregistrée et c’est elle qui préside aux déformations actives dans la région depuis le Haut-Atlas jusqu’au bassin Parisien.

**Mots clés :** Méditerranée occidentale / reconstructions cinématiques / retrait du panneau plongeant / zones de transfert / exhumation / croûte faible

1 Introduction

Slab dynamics is a first-order driver of the deformation of the overriding plates of subduction zones, especially when the subduction zone is constrained within a narrow space like the Mediterranean region (Carminati et al., 1998a; Wortel and Spakman, 2000; Facenna et al., 2001a, 2001b, 2003; Spakman and Wortel, 2004; Jolivet et al., 2009). The geometry of slabs at depth in this area is now well constrained thanks to seismic tomography and the mantle flow associated with slab retreat can be described using seismic anisotropy (Carminati et al., 1998a, 1998b; Wortel and Spakman, 2000; Piromallo and Morelli, 2003; Spakman and Wortel, 2004; Jolivet et al., 2009; Bezada et al., 2013; Facenna et al., 2014; Fichtner and Villasenór, 2015; Villasenór et al., 2015). Beside the rather simple back-arc extension related to slab retreat in the Liguro-Provençal basin and Tyrrhenian Sea, the most complex regions, such as the tight Betic-Rif Arc or the Alps-Apennines junction have been described with different dynamic models involving slab tearing and interactions between slabs (Platt and Vissers, 1989; Lonergan and White, 1997; Jolivet et al., 2006, 2008; Vignaroli et al., 2008; van Hinsbergen et al., 2014). Several key-events have been recognized in the Western Mediterranean such as the initiation of back-arc extension at ~ 32 Ma or the Late Miocene resumption of N-S compression in the Betic Cordillera that can be associated to the behavior of slabs at depth (Facenna et al., 2001a, 2001b; Vignaroli et al., 2008; Spakman et al., 2018). In order to test and discuss these conceptual, analogues and numerical models that address the interactions between slab dynamics and crustal deformation in the Mediterranean region, we propose a new set of detailed kinematic and tectonic reconstructions, obtained independently from these models.

Whether crustal deformation is driven by far-field forces guided by the resistant lithospheric mantle (lithospheric stress-guide) or by the mantle flowing underneath has been a debated question since the early days of the plate tectonics theory (Elsasser, 1968; McKenzie, 1969). This question is crucial in regions where different sources of forces are likely to be at work such as the complex back-arc regions of the Mediterranean realm. The Aegean region was used to propose different types of conceptual models, tested numerically, involving one or several of these different forces, mantle flow vs lithospheric stress-guide (McKenzie, 1972, 1978; Le Pichon and Angelier,
1981a, 1981b; Taymaz et al., 1991; Armijo et al., 1999; Wortel and Spakman, 2000; Spakman and Wortel, 2004; Govers and Wortel, 2005; Jolivet et al., 2009, 2013; Faccenna and Becker, 2010; Becker and Faccenna, 2011; Capitanio, 2014; Magni et al., 2014; Sternai et al., 2014). The localization and propagation of the North Anatolian Fault and the concomitant extension in the Corinth Rift extension in the overriding plate of the Hellenic subduction have for instance been diversely interpreted as (i) the result of rigid extrusion of Anatolia caused by the Arabia-Eurasia collision (McKenzie, 1972, 1978; Armijo et al., 1999), or (ii) a consequence of slab detachment and tearing, involving a component of basal shear by the asthenospheric mantle due to slab retreat (Jolivet et al., 2009, 2013; Sternai et al., 2014; Menant et al., 2016b). The possible role of large-scale convection with the interference of the Afar plume was also discussed (Faccenna et al., 2013b).

Similar questions can be addressed in the Western Mediterranean (Fig. 1) where large and fast displacements have been recorded since about 35 Ma and several drastic changes in the tectonic regime were documented. There, too, several models were proposed, involving slab retreat and associated small-scale asthenospheric flow as a main driver (Carminati et al., 1998a; 1998b; Rosenbaum et al., 2002; Faccenna et al., 2004; Rosenbaum and Lister, 2004; Spakman and Wortel, 2004; Faccenna et al., 2007; Jolivet et al., 2009; Vignaroli et al., 2009), stress transmission within the lithosphere causing buckling and strain localization (Casas Sainz and Faccenna, 2001; Dieforder et al., 2019), or control of crustal deformation by the flow of mantle due to large-scale convection dragging the slab northward (Spakman et al., 2018). These different drivers were probably all active at some period, but not all at the same time and their respective roles might have been more or less important through time. So far, several drastically different tectonic models were proposed for the long-term evolution of the Western Mediterranean: (i) lithospheric delamination (Platt and Vissers, 1989; Platt et al., 2003a, 2013), (ii) a single north-dipping subduction progressively retreating (Lonergan and White, 1997; Rosenbaum et al., 2002; Faccenna et al., 2004; Jolivet et al., 2006), (iii) two opposite subductions (Chalouan et al., 2001; Michard et al., 2002; Schettino and Turco, 2006; Vergés and Fernández, 2012; Lepèbre et al., 2018) or different combinations of some aspects of these models, with more or less slab retreat in the westernmost Mediterranean. Figure 1B shows four different configurations before the inception of back-arc extension (Michard et al., 2002; Rosenbaum et al., 2002; Lacombe and Jolivet, 2005; Vergés and Fernández, 2012; van Hinsbergen et al., 2014; Lepèbre et al., 2018). The differences pertain to the initial length of the subduction zone, either restricted to the latitude of the Balearic or continuing to the future Alboran region and the polarity of subduction, either a single NW-ward subduction or two subduction zones with opposite polarities. This initial situation has important consequences in terms of the dynamics of slab retreat as explored by Chertova et al. (2014) with 3-D numerical modelling. One of the goals of this paper is to investigate this question through a series of kinematic reconstructions with data independent of any dynamic model.

The only independent long-term record of these complex interactions is the geological record, and more specifically tectonics and magmatism. In such a complex 3-D environment, with fast displacements and sudden kinematic changes, a prerequisite to any discussion of the dynamic interactions is to possess a detailed account of the tectonic evolution through time. This is why we propose here a series of detailed tectonic reconstructions of the whole Western Mediterranean region, made with GPlates (Bfoyden et al., 2011), from the Apennines subduction to the Gibraltar arc, since the first evidence of back-arc extension in the Mediterranean some 35 Ma ago.

Our reconstructions are made backward step-by-step and built on independent geological and tectonic constraints, including published estimates of field-based shortening rates in convergence zones, estimates of extension rates in back-arc basins, paleomagnetic rotations, pressure-temperature-time history of metamorphic complexes, as well as information on the timing derived from stratigraphic and radiometric studies. The reconstructions are then integrated within the whole Mediterranean realm with the addition of the eastern Mediterranean reconstructions of Menant et al. (2016a).

We first describe the reconstructions and then discuss their geodynamic implications. The results show complex interactions between the Alps, the Apennines, the Pyrenees, the Betic Cordillera and the Rif, as well as the opening of back-arc basins. Back-arc basins formed at the emplacement of mountain belts that were locally superimposed by volcanic arcs and extensional basins, and were thus supported by thick, hot and weak continental crusts, leading to the formation of metamorphic core complexes and the exhumation of lower crustal domains during rifting. The initial configuration we obtain before the inception of slab retreat is intermediate between that of Vergés and Fernández (2012) and Michard et al. (2002) with two subduction zones with opposite polarities. The reconstructions also emphasize the role and timing of transfer fault zones accommodating tears in the slabs and their relations with magmatism. We discuss the different styles of transfer zones in the overriding plates above slab tears. Their integration in the wider Mediterranean framework and comparison of motion paths calculated in several kinematic frameworks with the mantle fabric deduced from seismic anisotropy shows that fast slab retreat was the main driver of back-arc extension in this region and that it prevented the transmission of compressional stresses across the Eurasia-Africa plate boundary zone. The situation changed at ~8 Ma when the slab retreating below the Gibraltar arc had migrated far enough westward for the N-S compression be felt again in the whole Western Mediterranean region.

2 Geodynamic context

Although the present-day setting of the Western Mediterranean (Fig. 1) is mostly characterized by compressional deformation along a N-S direction (Billi et al., 2011; Faccenna et al., 2014), the bulk geometry of this region was formed in a back-arc extensional environment between 35 and 8 Ma (Réhault et al., 1984; Wortel and Spakman, 2000; Faccenna et al., 2001a, 2001b; Rosenbaum et al., 2002; Spakman and Wortel, 2004). Extension is here the overriding plate response to the eastward or westward retreat of lithospheric slabs, which were subsequently fragmented in several segments subducting nowadays below Calabria, the Apennines and the Gibraltar
Fig. 1. Tectonic map of the Western and Central Mediterranean region (A). White dashed lines stand for the reconstructed cross-sections of Figure 3. Cal: Calabria, GA: Gibraltar Arc, MB: Marsili Basin, Pel: Peloritani, TA: Tuscan Archipelago, VB: Vavilov Basin. (B) Schematic presentation of four recent published kinematic hypotheses (Rosenbaum et al., 2002; Lacombe and Jolivet, 2005; Vergés and Fernández, 2012; van Hinsbergen et al., 2014) compared to the new model described in this paper.
Some basins were formed after 35 Ma, starting with rifting between Provence and Sardinia, shaping the Gulf of Lion passive margin and the oceanic domain of the Liguro-Provençal Basin, associated with the counterclockwise rotation of the more or less rigid Corsica-Sardinia block during the Oligocene and early Miocene (Réhault et al., 1984). Extension then jumped east of Corsica and Sardinia, forming the Tyrrenian Sea (Réhault et al., 1987; Kastens et al., 1988). Crustal thinning was extreme in the southern Tyrrenian Sea where the emplacement of oceanic crust in the Pliocene and Quaternary was classically proposed (Kastens and Mascle, 1990; Patacca et al., 1994; Crespo-Blanc, 1995; Alboran Sea between Iberia and the northern coast of Africa (Comas et al., 1992, 1999; Frizon de Lamotte et al., 2004; Mauffret et al., 2007; Medauri et al., 2014; Do Couto et al., 2016). During the first stages (27–20 Ma) extension in this region was mostly N-S and then changed abruptly some 20 Ma from N-S to E-W (Crespo-Blanc et al., 1994; Crespo-Blanc, 1995; Martinez-Martinez and Azañon, 1997; Jolivet et al., 2008; Crespo-Blanc et al., 2016). 8 Ma ago, extension slowed down drastically and the main tectonic regime became compressional (Weijermars et al., 1985; Mora, 1993; Augier et al., 2005c; Meijninger and Vissers, 2006; Billi et al., 2011).

The internal zones of the Western Mediterranean mountain belts are generally thought to belong to a former independent block, named AlKaPeCa, now dispersed by later back-arc extension (Bouillin et al., 1986). Its remnants are found at the periphery of the Alboran domain in the Betic Cordillera (Spain) and the Rif (Morocco), the Kabylies in the Tell (Algeria and Tunisia), the Peloritani range in Sicily and in Calabria (Bouillin et al., 1986; van Hinsbergen et al., 2014). Whether it constituted a single block or a series of individual smaller blocks is in fact unknown.

During this period dominated by back-arc extension, mountain belts were formed above the retreating subduction zones, the Apennines in the east, the Maghrebides in the south (Tell and Rif), and the Betics along the southern margin of Iberia. Slab retreat and coeval back-arc extension proceeded at high rates, ranging from 2 cm/yr to more than 10 cm/yr (Nicolosi et al., 2012; van Hinsbergen et al., 2014).

During the formation of these mountain belts (syn-orogenic stage) and during subsequent extension (post-orogenic stage), metamorphic core complexes (MCCs) were exhumed. The syn-orogenic period is characterized by a good preservation of high-pressure and low-temperature (HP-LT) metamorphic parageneses, while the late-orogenic period sees intense retrogression and often reheating, resulting in a more or less complete overprint of the HP-LT parageneses in high-temperature and low-pressure conditions (HT-LP) (Jolivet et al., 1998; Platt et al., 2013), an evolution resembling that of the Aegean region (Wijbrans and McDougall, 1988; Wijbrans et al., 1993; Trolet et al., 2001; Jolivet et al., 2003; Ring et al., 2010; Grasemann et al., 2012; Laurent et al., 2016; Roche et al., 2016). The exhumation of these MCCs is associated with intense shearing deformation and the development of km-thick strain gradients that affect large portions of the middle and lower crust. A good example is the case of the Betic Cordillera where exhumation was mostly associated with N-S-trending stretching lineations and top-to-the north sense of shear before 20 Ma and by E-W-trending lineations and top-to-the west sense of shear afterward (Azañon et al., 1997; Balanya et al., 1997; Jolivet et al., 2003, 2008; Williams and Platt, 2018). This change of direction is first observed in coeval basins deposited on top of the exhumed domains (Crespo-Blanc et al., 1994; Crespo-Blanc, 1995; Azañon and Crespo-Blanc, 2000; Augier et al., 2013).

This first-order evolution results from the convergence between Africa and Eurasia, but the driving mechanisms of crustal deformation can be understood in various ways. Stresses can be transmitted through the lithospheric stress-guide or from below by the asthenospheric mantle flowing underneath. Mantle flow can be caused by the large-scale convection or more local mantle flow related to slab retreat (Jolivet et al., 2009; Faccenna and Becker, 2010; Faccenna et al., 2013a; Faccenna et al., 2014; Sternai et al., 2014; Menant et al., 2016b). Mountain building and back-arc extension are often coeval along a given transect (Jolivet et al., 1994, 1996, 1998) but also in 3-D at the junction between two subduction zones such as the Alps and the Apennines, where the westward migration of the Alps thrust front and the eastward retreat of the Apennines front and opening of the Liguro-Provençal and Tyrrenian basins are coeval, probably linked with toroidal flow underneath (Maffione et al., 2008; Vignaroli et al., 2008, 2009).

During the last 35 Ma, several major tectonic changes are recorded. The first one is the progressive ending of compressional deformation in the Pyrenees and Central Iberian Range while it was still active in the Rif and the Betics, as well as in the Apennines (Comas et al., 1999; Vergès and Sábat, 1999; Jolivet and Faccenna, 2000; Rosenbaum et al., 2002; Vergès et al., 2002; Moutheureau et al., 2014). A second one is the inception of slab retreat all around the Mediterranean realm between 35 and 30 Ma (Jolivet and Faccenna, 2000). The third one is the end of back-arc extension some 8 Ma ago in the Alboran region (Augier et al., 2005c; Meijninger and Vissers, 2006; Billi et al., 2011; Augier et al., 2013; Janowski et al., 2017). All these events require a dynamic explanation. Are these modifications of the strain regime due to local events or parts of a single long-term mechanism, intrinsic to the convergence process?

In order to address these questions we first performed detailed tectonic reconstructions from 35 Ma to the Present and then discuss their implications in different kinematic frameworks in order to emphasize the individual drivers.

### 3 Previous reconstructions

Several reconstructions were published for the same region. After early proposals involving the rotation of Corsica and Sardinia (Argand, 1924; Carey, 1958), Alvarez et al. (1974) and Boccaletti and Guazzzone (1974) proposed models showing the successive opening of the Liguro-Provençal Basin
and then the Tyrrenian Sea. The first attempt using a plate tectonics approach was by Bayer et al. (1973) who proposed an identification of oceanic magnetic anomalies based on the compilation of two airborne surveys and made reconstructions of the Liguro-Provençal Basin where the Corsica-Sardinia block was however not rotating. Cohen (1980) proposed a series of reconstructions of the same region based on the geometry of transform faults, paleomagnetic data obtained in the margins of the domain and a compilation of geological data. These reconstructions involve the counter-clockwise rotation of a rigid Corsica-Sardinia block. Réhault et al. (1984) used the geometry of magnetic anomalies to infer the kinematics of opening and the position of transform faults, as well as paleomagnetic data supporting the rotation of Sardinia, the structure of the basin and its margins, and the timing of subsidence and heat-flow measurements to describe the evolution of the Liguro-Provençal Basin as a back-arc basin. Dewey et al. (1989) used a new study of the Atlantic fracture zones based on SEASAT data to propose an updated history of the Africa-Europe convergence. Within this large-scale kinematic framework they proposed detailed reconstructions of the Western Mediterranean including the Liguro-Provençal Basin, the Tyrrenian Sea and the Apennines. They used a new interpretation of the rotation of Corsica and Sardinia and the geological history of the basins and mountain belts around. Gueguen et al. (1998) proposed a more detailed tectonic evolution of the entire Western Mediterranean region back to the early Miocene based on the geometry of transform faults and the balancing of sections across the basins based on available seismic profiles. Rosenbaum et al. (2002) made reconstructions of the entire Western Mediterranean region since 30 Ma, using a variety of data types, from structural geology, metamorphic petrology, magmatic history, sedimentary basins, paleomagnetic data and geophysics (Fig. 1B). This was the first attempt using an integrated plate kinematics software (PLATYPLUS). Michard et al. (2002) proposed a different scenario where two subduction are facing each other (Fig. 1B), one being the future Apennines subduction and the second one, dipping to the SW the southern extension of the Alpine ocean. Jolivet et al. (2003) proposed reconstructions of the whole Mediterranean region to discuss the evolution of HP-LT metamorphic units and Lacombe and Jolivet (2005) showed a focus on the Western Mediterranean to discuss the relations between Corsica and Provence. Dézes et al. (2004) showed reconstructions of the same region to discuss the evolution of the West European Rift, Schettino and Turco (2006) focused their study on the Liguro-Provençal Basin. They did a detailed kinematic restoration using the identification of transform faults on magnetic anomaly maps to obtain the flow lines and position of rotation poles, an interpretation of the magnetic anomalies to date the opening and a balancing of crustal profiles. Mantovani et al. (2009) published detailed reconstructions of the evolution of the Tyrrenian Sea and the Apennines since the Middle Miocene. Van Hinsbergen et al. (2014) performed detailed reconstructions of the Western Mediterranean made with GPlates with the aim of addressing the cause of initiation of slab rollback in the Oligocene. These reconstructions are tested in particular with the amount of subducted lithosphere seen in seismic tomography data sets. Van Hinsbergen et al.’s (2014) work is the closest to ours in terms of methodology, except that we do not use seismic tomography to test the model and rely only upon the surface geological record as constraints. In the following we discuss the differences between the two models. More recently, Leprêtre et al. (2018) proposed new reconstructions of the westernmost Mediterranean based on a synthesis of geological studies in the Rif and Tell.

These reconstructions focused on the Western Mediterranean or only on the Liguro-Provençal Basin were published at the same time as reconstructions encompassing much larger regions such as all the belts born from the Tethys Ocean, including the Mediterranean realm (Dercourt et al., 1986; Ricou et al., 1986; Dercourt et al., 1993; Stampfli et al., 2002; Gaetani et al., 2003) or the whole of Western Europe, Arctic and Western Tethys (Ziegler, 1999). The most recent of these large-scale reconstructions was recently published by van Hinsbergen et al. (2019). It shows a detailed evolution of the Western Tethys and Mediterranean region since 200 Ma. These large-scale reconstructions show the long-term evolution of the Western Mediterranean but not the detail we need for discussing the driving parameters of crustal deformation since 35 Ma.

In all these reconstructions, paleomagnetic data gathered in the continental areas surrounding the basins are crucial constraints, together with the large geological and geophysical data sets. At variance with large oceanic domains, the use of oceanic magnetic anomalies is much less powerful because the classical Vine and Matthews’s (1963) type of anomalies are difficult to recognized in the oceanic domains of the Western Mediterranean, yet they have been used in some of these reconstructions (Bayer et al., 1973; Schettino and Turco, 2006). The nature of the crust in the “oceanic” domain is also quite disputed and several studies conclude to an atypical oceanic crust, if not only exhumed mantle. This is true of the Tyrrenian Sea (Prada et al., 2014, 2018) and of the Liguro-Provençal Basin (Rollet et al., 2002; Dannowski et al., 2020). Magnetic anomalies are indeed short and their symmetry on either side of a potential spreading axis is particularly unclear. Some of these anomalies clearly correspond to local large volcanoes and not to a typical oceanic crust. Similarly, using these anomalies to determine the geometry of transfer or transform faults is difficult. We thus do not rely on the magnetic anomaly pattern for our reconstructions.

4 Reconstruction method and model inputs

Reconstructions were made with the help of GPlates, a free plate kinematics software developed by EarthByte (http://www.gplates.org; Boyden et al., 2011). GPlates works with “features”, polygons or polylines (mostly polylines in our case), that are rotated about Eulerian rotation poles. For reconstructing the Western Mediterranean, and integrating these reconstructions in the whole Mediterranean framework, we used more than 400 such features (Fig. 2). Several tables are provided in the Supplementary Materials of this paper. Supplementary Material #1 contains (i) the geological, geophysical and paleomagnetic constraints used for the reconstructions, (ii) the associated list of references and (iii) the list of features (rigid polygons) used for the reconstructions. Supplementary Material #2 gives the GPlates rotation file with the rotation poles and angles of rotation, assorted with the bibliographic references (all included in the list of
The angles of rotation have been calculated to fit the amount of shortening or extension extracted from the listed reference. Supplementary Material #3 is an additional figure to discuss the significance of crossing motion-paths. The movie reconstructions-Medit-GPlates.mp4 shows the displacement of all blocks used for reconstructing this area.

Although the rotating features are rigid bodies, we take into account internal deformation of blocks by using polylines at their limits that rotate with different angles (Fig. 3A), thus accommodating shortening or extension like invan Hinsbergen et al. (2014). The general reconstruction procedure is also similar to that used by Menant et al. (2016a) for the eastern Mediterranean. Because we use polylines, the blocks are deformable at will. Adjusting the rotation angle simply increases or decreases the amount of shortening or extension. In between the two rotating block limits, which converge or diverge, the deformation is supposed to be pure shear in map view, homogeneously distributed across the deforming block. Converging block limits lead to crustal thickening and diverging block limits to extension. The amount of extension or shortening is a direct consequence of the imposed rotation angle. Thus, rifted margins such as the Gulf of Lion are reconstructed using balanced restoration as in Jolivet et al. (2015a, 2015b) and mountain belts in convergence zones are zones where crustal thickening is accommodated based on published balanced cross-sections.

The reconstructions are contained within the Mediterranean region that is surrounded by large plates, Africa, Eurasia, Iberia, and Arabia. We use the model recently published by Nirrengarten (2016) and Nirrengarten et al. (2018) and references therein for the motion of these large plates, an adaptation of Seton et al. (2012). This model uses oceanic magnetic anomalies in large oceans and takes into account the deformation of the margins during rifting. An alternative model was published by Macchiavelli et al. (2017), which does not differ much for the 35–0 Ma period. Besides the kinematic constraints imposed by the motion of the large plates around, we calculate kinematic parameters for the Western and Central Mediterranean domains using geological and paleomagnetic data (see Supplementary Materials #1 and #2 and references therein).

The kinematic history of the deforming region is constrained by the timing and rates of extension in basins and shortening in mountain belts, the activation and inactivation times of thrusts and detachments, the age of emplacement of oceanic crust, information on the migration of the magmatic arc during slab retreat (Fig. 3B). It is also constrained by the geometrical fit of oceanic domain margins like the Liguro-Provençal basin and by paleomagnetic data used to constrain the rotation of individual blocks such as Corsica-Sardinia (Gattacceca et al., 2007; Advokaat et al., 2014), oroclinal bending of Apennines (Sagnotti et al., 2000; Caricchi et al., 2014), rotations in Sicily (Speranza et al., 2003), rotations in the Gibraltar arc (Mattei et al., 2006; Crespo-Blanc et al., 2016) and a recent synthesis of formation of the tight Western Mediterranean arcs based on paleomagnetic data (Cifelli et al., 2016). Additional information comes from the pressure-temperature-time constraints obtained on exhumed metamorphic rocks that are used as a proxy for burial as a function of time, bringing some insights on the thermal regime and active geodynamic processes. Hence, HP-LT and HT-LP metamorphic events are diagnostic of syn- and post-orogenic environments, respectively. Kinematic indicators in the exhumed MCCs are also used to construct the kinematic model. We avoided using any a priori dynamic ideas to construct the kinematic model, using only published kinematic data for the large plates surrounding our study area and geological and paleomagnetic data for the internal kinematics. We thus consider that our kinematic model

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**Fig. 2.** Features (rigid polygons or polylines) used in the GPlates reconstructions shown with various colors. The list of these features is given in Supplementary Material #1 and the rotation file in Supplementary Material #2.
is as independent as possible of any dynamic considerations and can then be used to discuss dynamic processes.

Detailed geological cross-sections across mountain belts, their history of deformation (timing, shortening directions) and evolution of their foredeeps were used to constrain shortening at the periphery of the deforming region: Jura and Alps (Giannerini, 1980-1981; Sommaruga, 1997; Burkhard and Sommaruga, 1998; Lickorish and Ford, 1998; Scharf et al., 2013; Jourdon et al., 2014), Apennines (Pauselli et al., 2006; Boccaletti et al., 2011), Rif and Atlas (Gomez et al., 1998; Zarki et al., 2004; Benauqui-Mebarek et al., 2006; Chalouan et al., 2006; El Kadiri et al., 2006; Chalouan et al., 2008; Di Stasso et al., 2010; Vitale et al., 2014; Capella et al., 2017), Gibraltar arc (Rosenbaum and Lister, 2004; Crespo-Blanc and Frizon de Lamotte, 2006; Lujan et al., 2006; Pedrera et al., 2014; Sanz de Galdeano et al., 2015; Crespo-Blanc et al., 2016), Calabria and Peloritani (Bonardi et al., 2001; Heymes et al., 2010; Cirrincione et al., 2015), Baleares (Sàbat et al., 1997; Etcheve et al., 2016), shortening within Iberia (Vergés and Sàbat, 1999; Quintana et al., 2015), and Pyrenees (Muñoz, 1992; Meiggs et al., 1996; Muñoz, 2002; Mouthereau et al., 2014; Teixell et al., 2018).

The tectonic history of back-arc basins was also a major constraint with in particular exhumation kinematics and P-T-time evolution of MCCs, paleostress studies and structure of passive margins: Tyrrenhian (Cocchi et al., 2009), Corsica (Jolivet et al., 1990; Fournier et al., 1991; Jolivet et al., 1998; Brunet et al., 2000; Molli et al., 2006; Vitale Brovarone and Herwartz, 2013; Beaudoin et al., 2017), Tuscan archipelago (Jolivet et al., 1998), Valencia Basin (Roca et al., 1999; Etcheve et al., 2016; Etcheve et al., 2018), Gulf of Lion (Bache et al., 2010; Jolivet et al., 2015a; Moulin et al., 2015), Alboran region (Jabaloy et al., 1993; Platt et al., 2003a, 2003b; Booth-Rea et al., 2004, 2005, 2015; Augier et al., 2005a, 2005b;
Fig. 4. Reconstructions of the Mediterranean domain since 35 Ma. Colored symbols represent magmatic bodies (plutonic, volcanic and unspecified) and their magmatic series. The details of the Western Mediterranean is shown in Figure 5. For details on the Aegean-Anatolia region the reader is referred to Menant et al. (2016a, 2016b). Alps and Carpathians not precisely reconstructed, only indicative. Light blue: oceanic crust; green: exhumed mantle; orange: thinned continental crust; pink: high-temperature metamorphic core complexes; deep blue: high-pressure and low-temperature metamorphic complexes; yellow: areas with active shortening.
Fig. 4. Continued
Reconstructions were built progressively backward in time and are represented at key time steps, 5 Ma, 9 Ma, 15 Ma, 23 Ma, 28 Ma and 35 Ma (Figs. 4 and 5). Reconstructions of the Western Mediterranean were then integrated within a model encompassing the whole Mediterranean with the addition of the reconstructions of the Eastern Mediterranean published by Menant et al. (2016a). Note that the Alps and Carpathians were not reconstructed in this work and are shown only schematically, except for a part of the western Alps. On these reconstructions, the evolution of magmatic production was added with a differentiation of the magmatic series in order to discuss the interaction with geodynamic processes at mantle scale. The reader is referred to the work of Menant et al. (2016a) for the methodology of associating magmatic events to the reconstructions and for the compilation of original data for the Eastern Mediterranean. For the Western Mediterranean, the magmatic events were taken from the detailed compilations of magmatic events in the whole Western Mediterranean of Savelli (1988, 2002a, 2002b, 2015). These were completed by Serri et al. (1993) and Avanzinelli et al. (2009) for the evolution of magmatism in the Italian peninsula and periphery of the Tyrrenhian Sea. Ages of the Malaga dykes are from Esteban et al. (2013). The age of granitic bodies around Beni Bousera was taken from Rossetti et al. (2010). Réhault et al. (2012) detailed the Late-Eocene to Early Miocene magmatism in the northern part of the Liguro-Provençal Basin and more recent data were acquired by Lustrino et al. (2017). Maury et al. (2000), Coulon et al. (2002) and Abbassene et al. (2016) presented the evolution of magmatism along the northern margin of Africa and its relation to slab tearing. Duggen et al. (2004, 2005, 2008, 2009) detailed the evolution of magmatism in the westernmost Mediterranean in the Atlas, Rif and Alboran region, discussing the respective roles of subduction and hot spot volcanism. The ages of magmatism of the French Massif Central were taken from Nehlig et al. (2003).

5 Tectonic and geodynamic evolution from 35 Ma to the present

The reconstructed paleo-tectonic maps at key-periods come with lithospheric-scale cross-sections along four major transects (I to IV, Figs. 6A–6D) that represent the main geodynamic processes at work since the end of the Eocene; their locations are shown in Figure 1. In the following, we describe these key-periods and insist on the transitions in between. The chosen time-steps are just snapshots in a continuous evolution and the transition between these is equally important.

5.1 35–28 Ma, from late Eocene to middle Oligocene (Figs. 5a and 5b)

The earliest stage of our reconstructions (35 Ma) corresponds to the Priabonian. The backward step-by-step reconstruction leads to a geometry of subduction zones where the Mesozoic Tethyan lithosphere is consumed in two different trenches. The longest one runs from the zone of transition from the Alps to the future Apennines all the way to the southeast of the Baleares. The Tethyan oceanic lithosphere sinks north-westward underneath Corsica, Sardinia and the AlKaPeCa block. The second subduction zone has an opposite vergence. The subducting plate dips underneath the westernmost part of AlKaPeCa along a NS-trending trench in the Alboran domain. The trench probably extends further toward the northeast but its possible connection with the then-closed Ligurian Ocean as in Michard et al. (2002) and Chalouan and Michard (2004) is uncertain. This subduction zone has consumed the partly oceanized basin preserved in the Nevado-Filábride complex in the Bédar Macael unit (Puga et al., 2017).

The oceanic domain between Iberia and Africa is represented on the reconstructions based on the hypotheses proposed by Frizon de Lamotte et al. (2011), Vergès and Fernández (2012), Leprière et al. (2018), Fernández et al. (2019) or Pedreira et al. (2020). Because the relative motion during the Jurassic and the early Cretaceous between Africa and Eurasia was highly oblique with a left-lateral component, these authors show a series of short spreading centers, partly oceanized and with exhumed mantle in the ocean-continent transition and separated by transform faults. This domain is now partly included in the Betic nappe stack. Portions with partly oceanized crust or exhumed mantle are found in the Bédar-Macael unit of the Nevado-Filábride complex or the Ronda and Beni Bousera peridotite massifs on the Alpujárride complex. It is progressively subducted and partly accreted through the subsequent stages of the reconstructions.

The Priabonian sees a major transition in the Pyrenees and Languedoc (Séranne, 1999; Grool et al., 2018), characterized by the last thrusting episodes along the northern Pyrenean thrust front that is reworked by left-lateral strike-slip faults and associated basins between the Pyrenees and Provence fold-and-thrust belt. These strike-slip faults connect further north with the West European Rift System (WERS) (Séranne, 1999). We assume that the overall crustal-scale structure seen on seismic profiles of the Pyrenees today (Chevrot et al., 2018) was to the first order established at the end of the Eocene, despite some more shortening until the Late Oligocene — Early Miocene in the South Pyrenean Zone (Munoz et al., 2018). We also assume that this structure was present in the eastern Pyrenees at the time the Gulf of Lion passive margin began to form (see cross-section II-’I’ and section III-’I’ in Fig. 6B). During the Oligocene, rifting in the Gulf of Lion led to the collapse of the eastern part of the Pyrenees. Jolivet et al. (2020) proposed that this rifting episode involved extraction of upper mantle and lower crust to form the Gulf of Lion’s metamorphic core complex. During this period, Corsica belongs to an active compressional orogen sandwiched between the future Apennines subduction, then dipping toward the NW, and the Provence fold-and-thrust belt (Vially and Tremolières, 1996; Lacombe and Jolivet, 2005) (see cross-section I-’1’ on Fig. 6A). The alternative solution of a flip of subduction from a south-dipping subduction in Provence to a north-dipping subduction south of Corsica and Sardinia as proposed by Schettino and Turco (2006) would make slab retreat almost coeval with subduction initiation, which is not likely. The Paleozoic continental basement of Western Corsica overtrusts the deformed cover of Provence, shortened by a series of north- and south-vergent thrusts, such as in the Sainte Baume and Sainte Victoire massifs (Le Pichon et al., 2010; Oudet et al.,...
Fig. 5. Reconstructions in map view at selected periods since the end of the Eocene. 5a: Priabonian (35 Ma), 5b: Late Rupelian-early Chattian (28 Ma); 5c: Early Aquitanian (23 Ma), 5d: Burdigalian (18 Ma), 5e: Langhian (15 Ma), 5f: Tortonian (9 Ma), 5g: Zanclean (5 Ma), 5h: Present-day. Alp: Alpujarride, Cb. O.: Cobdar Ocean, Elb: Elba, ETSZ: East Tenda Shear Zone, GB: Granada Basin, Gi: Giglio, GoL MCC: Gulf of Lion Metamorphic Core Complex, HO: Huercal Overa Basin, Lan: Languedoc, MB: Marsili Basin, MC: Monte Cristo, NF: Nevada-Filàbride, RP: Ronda peridotite, SA: Sierra Alhamilla, SG: Sierra de Gador, SL: Schistes Lustrés, SN: Sierra Nevada, STB: Sorbas-Tabernas Basin, VB: Vavilov Basin, WAB: West Alboran Basin. I-I', II-II', III-III' and IV-IV' are the traces of the cross-sections of Figure 6, also positioned on the map of Figure 1 for the present-day situation.
Fig. 5. Continued
Fig. 5. Continued.

A. Romagny et al.: BSGF 2020, 191, 37
Fig. 5. Continued.
2010; Rangin et al., 2010; Espurt et al., 2012; Fournier et al., 2016). The HP-LT metamorphic rocks of Alpine Corsica are the southernmost extension of the Ligurian Schistes Lustrés Nappe of the Alps (Caron et al., 1981; Faure and Malavieille, 1981; Mattauer et al., 1981; Malavieille, 1983; Gibbons and Warburton, 1986; Warburton, 1986; Fournier et al., 1991; Malavieille et al., 1998; Molli et al., 2006; Molli and Malavieille, 2010). They record their last HP-LT overprint at ~34 Ma in the Alps (Vitale Brovarone and Herwartz, 2013). Exhumation in Alpine Corsica is mostly accommodated by low-angle detachments that bring non-metamorphosed units directly on top of the HP-LT Schistes Lustrés Nappe (Jolivet et al., 1990; Fournier et al., 1991; Beaudoin et al., 2017). From 32 Ma onward, the thrust front migrates together with the retreating slab and the tectonic units once belonging to the accretionary wedge are then transferred to the back-arc region and exhumed mostly by extension there (Jolivet et al., 1991; Daniel et al., 1996; Brunet et al., 2000; Maggi et al., 2012; Beaudoin et al., 2017). This situation is typical of the Mediterranean setting and is also observed in the Aegean region, north of the Hellenic trench (Fig. 4) (Jolivet and Brun, 2010). In Figure 6A, we show only the 35 and 23 Ma stages and some shortening was active between 35 and 32 Ma, so that the retreat active between 32 and 23 is not expressed.

Farther south, the AlKaPeCa block also records the end of HP-LT events in the Betic Cordillera (Bessière, 2019). HP-LT metamorphism in the Alpujárride and Nevado-Filabrid complex results from subduction of portions of the continental margin of Iberia and of the AlKaPeCa block. The width of the accretionary wedge is not known. We consider that the peak of pressure is attained around 40 Ma in the Nevado-Filabrid complex and the Alpujárride complex (Platt et al., 2005; Li and Massonne, 2018; Bessière, 2019). In the Alpujárride complex available ages are dispersed with concentration around 20 Ma but the oldest ages are Eocene, around 40 Ma (Platt et al., 2005; Bessière, 2019). In the underlying Nevado-Filabrid complex, the age of the peak pressure is debated. Augier et al. (2005a) used the “Ar/Ar” method on white micas crystallized along the decompression path from the peak of pressure in the P-T field of the eclogite facies to the greenschist facies and they show a systematic decrease of ages from about 30 Ma to about 14 Ma. They concluded that the peak of pressure was attained in the Eocene. López Sánchez-Vizcaíno et al. (2001) and Platt et al. (2006) instead obtained younger middle Miocene ages using the U/Pb method on zircons and the Lu/Hf on garnets that they attributed to the maximum pressure. More recently, Li and Massonne (2018) dated the peak of pressure in the Bédar-Macael unit of oceanic or hyper-extension affinity, based on the U/Pb method on monazite, to ~40 Ma, which better fits the results obtained by Augier et al. (2005a). We thus consider the young ages obtained by López Sánchez-Vizcaíno et al. (2001) and Platt et al. (2006) as exhumation ages (see Bessière, 2019 for a more detailed discussion). Exhumation-related shearing in the Alpujárride complex is N-S or NE-SW with a top-NE sense of shear and the peak of pressure dates back to 38 Ma, according to Bessière (2019). Exhumation is accommodated by extension and detachments such as the Malaguide-Alpujárride Contact (Lonergan and Platt, 1995) (MAC in Fig. 5A), a large detachment marking the contact with the Malaguide complex above (Platt and Vissers, 1989; Augier et al., 2005a; Platt et al., 2013; Williams and Platt, 2018) and series of detachments inside the nappe stack of the Alpujárride Complex (Azañón et al., 1997; Azañón and Crespo-Blanc, 2000). The direction of extension during this period is N-S or NE-SW and most of the deformation coeval with exhumation is non-coaxial with a top-to the north asymmetry (Jolivet et al., 2008; Augier et al., 2013). The position of the AlKaPeCa block in the reconstructions at 35 Ma is the result of removing the extension that has occurred since that period to return to a normal thickness of 30 km. The finite displacement is thus a minimum and the initial position at 35 Ma could then be farther to the NE, a situation that would not be much different from that proposed in van Hinsbergen et al. (2014).

The AlKaPeCa block has not yet collided with the northern margin of Africa, but the space left in between is very narrow (Leprette et al., 2014). Compression is also active during this period in the Atlas that records a first period of shortening along its entire length from Morocco to Tunisia (Chalouan et al., 2008; Frizon de Lamotte et al., 2008, 2011; Leprette et al., 2018). The beginning of this period is thus characterized by a generalized compressional regime active from the Atlas all the way to the Pyrenean-Cantabrian belt (Jolivet et al., 2016). Then, from 32 Ma onward, the subduction regime changes totally and slab retreat starts (Jolivet and Faccenna, 2000). Shortening however continues in the Southern Pyrenees with the propagation of the southern thrust front until the early Miocene (Muñoz, 2002; Jolivet et al., 2007; Labaume et al., 2016; Muñoz et al., 2018) while the eastern Pyrenees record a large-scale episode of exhumation and uplift coeval with the inception of rifting in the Gulf of Lion around 30 Ma (Morris et al., 1998; Fitzgerald et al., 1999). This change of subduction regime is associated with the development of a discontinuous magmatic arc with calcalkaline affinity including plutonic bodies with adakitic characteristics such as the Esterellite in Provence (Réhault et al., 2012) (Fig. 4A). The first subduction-related magmatism develops in Sardinia as soon as 38 Ma (Lustrino et al., 2009).

5.2 28–23 Ma, Oligocene, Late Rupelian-Early Chattian to Oligocene-Miocene boundary (Figs. 5B and 5C)

The early Oligocene corresponds to the first stage of backarc extension in the whole Mediterranean around 30–32 Ma (Jolivet and Faccenna, 2000), which is active everywhere above the SW-NE striking subduction zone consuming the remaining Ionian oceanic lithosphere. Rifting starts to the northwest of Corsica and Sardinia with low-angle detachments shaping the Gulf of Lion passive margin (Jolivet et al., 2015a, 2019). Extension with southeast-dipping low-angle detachments is also active in Alpine Corsica, exhuming the HP-LT metamorphic units of the Schistes Lustrés (East Tenda Shear Zone) and Tenda Massif (Jolivet et al., 1990, 1991; Fournier et al., 1991; Beaudoin et al., 2017). During the course of slab retreat, the accretionary wedge in Corsica retreats eastward, followed by the back-arc extensional domain that is instead widening. The distance between the trench and the magmatic arc decreases with time, an indication of the increasing steepness of the slab explaining the narrowness of the wedge (Figs. 6A and 6B) (Jolivet et al., 1998; Brunet et al., 2000). Extension is also active in Sardinia with the formation of tilted
blocks controlled by northwest-dipping normal faults (Cherchi and Montadert, 1982; Casula et al., 2001). N-S extension exhumes HP-LT metamorphic units of the Alpujárride in the future Betic-Rif orogen (Azañon et al., 1997; Martínez-Martínez and Azañon, 1997; Azañon and Crespo-Blanc, 2000). Coevally, a southward migration of the southern thrust front of the Pyrenees is recorded (Jolivet et al., 2007; Labaume et al., 2016). A calc-alkaline magmatic arc develops from Sardinia (Lustrino et al., 2009) to the northeastern Valencia Basin (Maillard et al., 2020) (Fig. 4A). Evidence of magmatic product then shift toward the south across the transfer zone between Sardinia and the Baleares Islands.

5.3 23–18 Ma, Oligocene-Miocene boundary to Burdigalian (Figs. 5C and 5D)

At 23 Ma, a large oceanic domain is still to be consumed by subduction south of the AlKaPeCa terranes. Slab retreat proceeds mostly southward at the longitude of Algeria and Tunisia. Farther west in the future Betic-Rif domain, recorded extension is still mostly N-S in the first part of this period with detachments accommodating the exhumation of the HP-LT Alpujárride complex in the future eastern Betics and part of the Rif (Crespo-Blanc et al., 1994; Negro et al., 2005; Jolivet et al., 2008).

In the west of the Betics, HP-LT metamorphic rocks are exhumed below the MAC detachment and above the west-directed basal thrust of the Ronda peridotite and Dorsale Calcaire (Platt et al., 1998, 2003b; Mazzoli and Martin-Algarra, 2011; Mazzoli et al., 2013; Précigout et al., 2013; Frasca et al., 2016; Gueydan et al., 2019). The nature of the domain subducting below the Alpujárride units is partly unknown. It could be partly oceanic and partly a highly thinned continental crust.

At this period, a high-temperature metamorphic event and a fast exhumation episode are recorded in the Western Betics and the Rif, attested by a clustering of radiometric ages between 23 and 19 Ma with a variety of geochronological systems (Loomis, 1975; Priem et al., 1979; Zeck et al., 1989, 1992; Monié et al., 1994; Sosson et al., 1998; Platt and Whitehouse, 1999; Sánchez-Rodríguez and Gebauer, 2000; Zeck and Williams, 2001; Platt et al., 2003a, 2003b, 2005; Whitehouse and Platt, 2003; Esteban et al., 2004, 2011; Michard et al., 2006; Rossetti et al., 2010; Frasca et al., 2017; Homonay et al., 2018; Li and Massonne, 2018; Bessière, 2019; Gómez-Pugnaire et al., 2019). It is recorded in all individual nappes of the Alpujárride, from east to west (Esteban et al., 2004; Platt et al., 2005; Li and Massonne, 2018; Bessière, 2019). The significance of this clustering of ages around 20 Ma is still under discussion. It is classically interpreted as a resetting of all chronometers due to a thermal pulse related to an episode of slab detachment or slab tearing coeval with the overthrusting of the Alpujárride complex, including the Ronda peridotite, onto the continental margin of Iberia (Mazzoli and Martin-Algarra, 2011; Mazzoli et al., 2013; Gueydan et al., 2019). It could indeed be caused by the HT-LP event in the western Betics, but this event is not strong enough to fully overprint the former HP-LT parageneses in the eastern Betics where they are quite well preserved (Bessière 2019). Alternatively, it could correspond to an exhumation event synchronously recorded in the whole Betic domain (Bessière 2019). The coeval fast exhumation of all units still buried make them cross the closure temperature of all geochronological systems.

In the Gulf of Lion, this period is that of rifting and exhumation with formation of a MCC made of lower crust, below northwest-dipping detachments east of the Catalan transfer zone (Jolivet et al., 2015a; Canva et al., 2020; Maillard et al., 2020) (Figs. 5C and 6B). Fast rotation of Corsica and Sardinia follows, coeval with the emplacement of oceanic crust or exhumed mantle in the Liguro-Provençal basin (Vigliotti and Kent, 1990; Gattacceca, 2000; Speranza et al., 2002; Gattacceca et al., 2007; Maffione et al., 2008; Dannowski et al., 2020). The previously formed Pyrenean chain is rapidly collapsing in this region and extensional structures rework the Provence fold-and-thrust belt (Gorini et al., 1993; Séranne, 1999). In the southern Pyrenees, the last south-vergent thrusts propagate in the Ebro basin until about 20 Ma (Munoz, 2002; Vergès et al., 2002; Jolivet et al., 2007; Bosch et al., 2016; Labaume et al., 2016). Slow extension is active in the Valencia Basin associated with intense magmatism, especially in the transition zone with the Gulf of Lion through a series of NW-SE striking dextral transfer faults (Maillard and Mauffret, 1999; Maillard et al., 2020). Magmatism is still active in the Sardinia volcanic arc and northward from offshore Corsica to the Ligurian Sea (Lustrino et al., 2009; Réhault et al., 2012).

5.4 18–15 Ma, Miocene, Burdigalian to Langhian (Figs. 5D and 5E)

In the Burdigalian, an oceanic space is still open between the southward migrating AlKaPeCa block and the northern African margin, but an accretionary wedge is developing at the expense of the Flysch units that will then overthrust the margin (Lepêtre et al., 2014). The same geometry can be found further west, west of the retreating Gibraltar arc (Crespo-Blanc and Frizon de Lamotte, 2006). In the overriding domain, back-arc extension is active with the continuing opening of the Liguro-Provençal basin and the Algerian basin. The oceanic crust of the Algerian basin progresses westward, following the migration of the Alboran domain, which width increases because of back-arc extension. The opening is associated with NW-SE trending transfer faults that accommodate the differential rotation of the Corsica-Sardinia block on the one hand and the AlKaPeCa block on the other hand (Mauffret et al., 1995; Maillard and Mauffret, 1999; Maillard et al., 2020). Emplacement of oceanic crust follows hyper-extension of the Gulf of Lion margin and exhumation of mantle and lower crust of the Gulf of Lion MCC below northwest-dipping detachments (Jolivet et al., 2015a; Moulin et al., 2015). In the Liguro-Provençal and Algerian basins, oceanic crust is emplaced but no distinct ridge, nor clear magnetic anomaly pattern can be recognized (Rollet et al., 2002). Recent surveys suggest that the crust once attributed to oceanic accretion is in fact exhumed mantle with localized magmatism (Dannowski et al., 2020). Extension is active in Alpine Corsica with east-dipping detachments, completing the exhumation of the HP-LT metamorphic units of the Schistes Lustrés (Jolivet et al., 1991; Daniel et al., 1996). One of these detachments is the East Tenda Shear Zone, active from ∼ 30 Ma to 21 Ma in the ductile
Fig. 6. Reconstructed cross-sections at selected periods. See cross-sections location on Figure 1. The structure of the Pyrenees is adapted from Chevrot et al. (2018). (A) Section across the Provence fold-and-thrust belt, the Liguro-Provençal basin, Corsica, the Tyrrhenian Sea and the Tuscan Archipelago and, finally the Apennines. (B) Section across the Gulf of Lion passive margin, the Liguro-Provençal Basin, Sardinia, The Southern Tyrrhenian Sea, Calabria and the Calabrian subduction zone. 6c: section across the Pyrenees, the Catalan Range, the Valencia Trough, the Balearic Islands, the Algerian Basin, the north African margin of Algeria and the Tell. 6d: section across the Gulf of cadiz accretionary wedge, the Gibraltar Arc, the Alboran Sea. Shorter sections show a parallel E-W onland line across the Betic Cordillera.
Fig. 6. Continued.
field and in brittle conditions afterward (Daniel et al., 1996; Rossetti et al., 2015; Beaudoin et al., 2017), controlling the deposition of sediments into the asymmetric Saint Florent basin from the Burdigalian onward (Ferrandini et al., 1996; Cavazza et al., 2007). In the Betic and Rif, back-arc extension is also active behind the future Gibraltar arc thrust front. The exhumation of the Nevada-Filabride Units in the Sierra Nevada-Sierra de los Filabres MCC has started below the Filabres detachment with a top-to-the west kinematics, mostly accommodated by ductile deformation (Jabaloy et al., 1993; Augier et al., 2005c, 2005d). As mentioned above, we consider here that the middle Miocene ages obtained in the Nevada-Filabride complex and interpreted as dating the HP-LT metamorphism in this complex (López Sánchez-Vizcaino et al., 2001; Platt et al., 2006) as exhumation ages (see a discussion in Bessière et al., this volume).

The 18–20 Ma period corresponds to the age of a change in the direction of extension and exhumation that switches from N-S to E-W, following the westward retreat of the slab subducting below the Betic-Rif orogen (Jolivet et al., 2006, 2008). At about 15 Ma, an almost continuous magmatic arc is active from the Ligurian Sea to Corsica, then Sardinia and along the northern African margin with potassic calc-alkaline affinity (Fig. 4A).

5.5 15–9 Ma, Miocene, Langhian to Tortonian (Figs. 5E and 5F)

15 Ma is a key-date in the evolution of the Western Mediterranean region. It immediately follows the completion of the collision of the AlKaPeCa block, carried by the overriding plate during the southward retreat of the subduction zone, with the northern margin of Africa and complete resorption of the Tethys remnants there, after the opening of the Liguro-Provençal basin (Chamot-Rooke et al., 1999; Leprêtre et al., 2014). This collision has been diachronous as shown on the reconstructions but the oceanic space north of the present Tell definitely closes at about 15 Ma. No southward retreat is then possible after this final docking of AlKaPeCa on Africa and the slab only retreats eastward along an AlKaPeCa on Africa and the slab only retreats eastward along a transfer fault north of Sicily (Rosenbaum and Lister, 2004) or westward along the northern margin of Africa. Magmatism, essentially granitoids, develops in northern Algeria and Tunisia with potassic calco-alkaline affinities and then migrates westward along the margin to reach the southern margin of the Alboran Sea with transitional affinity at 9 Ma and alkaline affinity afterward (Fig. 4B). This migration has been interpreted as a witness of the progressive tearing of the slab from east to west (Maury et al., 2000; Coulon et al., 2002) supported by tomographic imaging showing a detached slab (Fichtner and Villasenor, 2015) or no slab (Spakman and Wortel, 2004) below the Algerian margin nowadays. Near the front of subduction, the Betic-Rif accretionary wedge continues to form above the retreating slab at the expense of the passive margins. In the Internal Zones of the Betics, the exhumation of the Sierra Nevada MCC below the Filabres detachment is still active with top-to-the west shear sense across the ductile-to-brittle transition and the last synkinematic metamorphic minerals form (Jabaloy et al., 1993; Augier et al., 2005a). Last increments of motion occur in the brittle field still with a dominant top-to-the-west sense of shear until 12 Ma. At that time, most of the extensional intramountain basins present in the eastern Betics form above extensional detachments with different kinematics and infill dynamics (Meijninger and Vissers, 2006; Augier et al., 2013; Do Couto et al., 2014). The opening of the Algerian Basin proceeds with a westward migration following the westward retreat of the slab below the Gibraltar arc (Mauffret et al., 2004; Driussi et al., 2015). Further east, the retreat of the Apennines slab is stalling for a few Myr after the opening of the Liguro-Provençal basin and before the opening of the Tyrrhenian Sea (Faccenna et al., 2001a, 2001b, 2003).

One puzzling observation remains difficult to explain, the middle Miocene thick-skinned shortening event recorded in Ibiza and Mallorca, in the Balearic islands (Fig. 5E). This short event is well documented in the field and offshore (Sibat et al., 1997; Rocca, 2001; Etcheverry et al., 2016). It comes after an episode of Oligocene and early Miocene rifting and before a second episode of extension at the end of the middle Miocene with a component of dextral motion along the Emile Baudot escarpment (Driussi et al., 2015; Etcheverry et al., 2016). The Oligocene-early Miocene extension is coeval with back-arc opening in the Liguro-Provençal basin and the transtensional episode with the opening of the southern Algerian basin and fast migration of the Alboran block toward the west. So, this short compression is recorded in an overall extensional period. Etcheverry et al. (2016) note that it happens at the time of docking of the AlKaPeCa block on the north African margin. Compressional stresses may have then been transferred across the oceanic Algerian basin from the Kabylian to the Balearic islands.

5.6 9–5 Ma, Miocene, Tortonian to Zanclean (Figs. 5F and 5G)

The N-S compression recorded in the Pliocene in the Betics was first established in the Late Tortonian, some 8 Ma ago. At 9 Ma, the Sierra Nevada MCC completes its exhumation as recorded by low-T thermochronology (Johnson et al., 1997) still controlled by tectonic denudation and extension due to westward slab retreat (Galindo-Zaldívar et al., 1989; Augier et al., 2005a). From ~8 Ma, a drastic change is well recorded in the eastern Betics where part of intramountain basins (Sorbas, Tabernas, Huercal-Overa) are inverted, and the MCCs of the Sierra de Los-Filabres-Sierra Nevada, Sierra Alhamilla, Sierra de Gador are uplifted with respect to the intervening basins by a series of long wavelength folds (Comas et al., 1999; Meijninger and Vissers, 2006; Iribarren et al., 2009; Augier et al., 2013; Janowski et al., 2017). At 9 Ma, the tight Gibraltar arc seen today was not yet formed and the reconstructions show a N-S arrangement of the various tectonic units seen today around the sharp bend (Fig. 5F) and during this period, the Gibraltar arc progressively reached its present-day curvature (Crespo-Blanc et al., 2016). This is associated with the propagation of the oceanic crust of the Algerian Basin toward the west and continuing E-W extension in the Alboran region and the initiation of the strike-slip regime (Mauffret et al., 2004; Driussi et al., 2015). The Southern Tyrrhenian Sea opens during this period east of Sardinia with the formation of the Vávilov Basin, mostly by mantle
exhumation and some localized volcanism (Prada et al., 2014, 2016, 2018), while the thrust front of the Appennines propagates eastward. Extension is also active east of Corsica in the northern Tyrrhenian Sea, with east-dipping detachments exhuming granitoids and MCCs, such as in the islands of Elba, Monte Cristo and Giglio (Keller and Pialli, 1990; Jolivet et al., 1998; Collettini and Holdsworth, 2004). During this period, the Messinian salinity crisis represents a short dessication event just before the return of seawater in the Zanclean (Hsü et al., 1973; 1978; Clauzon et al., 1996; Krijgsman et al., 1999; Jolivet et al., 2006; Lofi et al., 2010; Bache et al., 2011; Garcia-Castellanos and Villaseñor, 2011) that occurred during the rifting of the western Tyrrhenian basin (Lymer et al., 2016). Alkaline magmatism develops in the French Massif Central (Fig. 4B) (Nehlig et al., 2003).

The main change during this period is the return to N-S shortening in the Eastern Betics, while E-W extension is still active in the Granada basin and the Gibraltar Arc still retreating westward.

5.7 5–0 Ma, Pliocene, Zanclean to Present (Figs. 5G and 5H)

The main changes between the Early Pliocene and the Present is the fast opening of the Southern Tyrrhenian Sea, namely the Marsili Basin, as well as the onset of shortening along the northern margin of Africa, Sicily and southern margin of France, offshore between the Gulf of Lion and Gulf of Genova (Mauffret et al., 2004; Billi et al., 2011; Maillard and Mauffret, 2013). N-S compression is recorded also during the Pliocene in the High Atlas (Frizon de Lamotte et al., 2011; Lanari et al., 2020a, 2020b), as well as in the Betics where large wavelength folds amplify the domes of the Sierra Nevada, Sierra Alhamilla, Sierra de Gador (Janowski et al., 2017). In this overall N-S compressional context, E-W extension is still active, especially in the Betics Cordillera, west of the Sierra Nevada metamorphic dome, with active normal faults along the boundary between the metamorphic dome and the Granada Basin (Galindo-Zaldivar et al., 1999; Booth-Rea, 2001). This period also sees the initiation of the left-lateral Trans-Alboran Shear Zone and associated magmatism (Hernandez et al., 1987; de Larouzière et al., 1988; Stich et al., 2006; Estrada et al., 2017; Lafosse et al., 2018; d’Acremont et al., 2020; Lafosse et al., 2020). N-S compression and E-W extension is also associated with active conjugate sinistral and dextral strike-slip faults and compressional ridges in the eastern and central part of the Alboran Sea (Booth-Rea et al., 2003, 2004; Martinez-Garcia et al., 2013; Estrada et al., 2017; Lafosse et al., 2018; d’Acremont et al., 2020). This N-S shortening was progressively established over the whole Western and Central Mediterranean triggering today the compressional earthquakes and active faults mapped offshore (Deverchère et al., 2003; Billi et al., 2011). N-S or NNW-SSE shortening is recorded in the High Atlas and the rate of uplift increases after 6 Ma (Frizon de Lamotte et al., 2000; Benouali-Mebarek et al., 2006; Lanari et al., 2020a, 2020b) and becomes more NW-SE in the north (France) (Cornet and Burlet, 1992; Dézes et al., 2004; Baize et al., 2013). Zitelini et al. (2019) recently brought observations in favor of a compressional reactivation of the southern Tyrrhenian Sea during the Pliocene. Coevally, the Calabria and Gulf of Cadiz accretionary wedges continuously form until the Quaternary (Gutscher et al., 2002; Polonia et al., 2011; Gutscher et al., 2012, 2017). Magmatism is widely distributed within the whole studied region during this time interval with principally alkaline chemistry, except in the east along the Italian peninsula and the nearby offshore domain with the development of calc-alkaline and tholeiitic volcanism above the Apennines subduction zone (Fig. 4B). The recent period also shows the development of alkaline magmatism in the westernmost Mediterranean, best explained by the northward migration of a finger of hot asthenospheric mantle coming from the Canary hot spot (Duggen et al., 2004, 2009).

6 Comparison with the Eastern Mediterranean

The reconstructions at the scale of the Mediterranean region (Figs. 4A and 4B) show the coeval evolution of the Western Mediterranean basins and Aegean domain (see Menant et al., 2016a, for details on the Aegean domain). The Aegean Sea was formed during the same period as the Western Mediterranean Basins. Fast slab retreat and related extension starts at ~32–35 Ma and migrates southward during the southward retreat of the Hellenic subduction. The main difference between these two regions is that the Aegean domain never reached the stage of oceanic crust emplacement despite more than 500 km of southward retreat since the end of the Eocene (Jolivet and Brun, 2010). A series of metamorphic core complexes form during the Oligocene and the Miocene starting from the Rhodope in the north and migrating southward toward the Cyclades and Crete. Extension had in fact started earlier in the Rhodope massif with the exhumation of a large MCC (Koumov et al., 2020) but without clear evidence for significant slab retreat such as the migration of a volcanic arc (Jolivet and Brun, 2010). One of the salient features of the Aegean region is the formation of slab tears at around 15 Ma leading to a fast clockwise rotation of the Hellenides and part of the Cyclades until 8 Ma (Kissel and Laj, 1988; de Boorder et al., 1998; Kissel et al., 2002; van Hinsbergen et al., 2005; 2006; Dilek and Altunkaynak, 2009; Jolivet et al., 2015a, 2015b). This same period (15–8 Ma) is also characterized by slab tearing and fast rotations/displacement in the Western Mediterranean, as the western part of the docked AlKapCa block starts its westward migration along the northern margin of Africa at around 15–16 Ma. This tectonic evolution is accompanied by a migration of magmatism from east to west along the north African margin (Maury et al., 2000; Do Couto et al., 2016), similarly to the magmatic activity in the western Anatolia-Aegean domain, also as a response to slab tearing (Menant et al., 2016a, 2016b). This is particularly the case of the Miocene Aegean granitoids (Jolivet et al., 2015b; Menant et al., 2016b) which show a westward migration in the middle-late Miocene, superimposing on the global N-S migration of the magmatic activity in the whole Aegean domain in response to slab retreat since 30–35 Ma (Pe-Piper and Piper, 2006; Jolivet and Brun, 2010). The coeval evolution of these two distant domains probably signs a common, global triggering cause for slab tearing in the Mediterranean region.
A second common feature to the Aegean and Western Mediterranean domain is the progressive generalization of alkaline volcanism from 9 Ma to the Present, see also Wilson and Bianchini (1999), Lustrino et al. (2011) and Melchiorre et al. (2017). Through time one sees a progressive evolution from calc-alkaline to highly-potassic calc-alkaline and then to alkaline in most regions, which could be the result of the progressive slab retreat aided by slab tearing, leading to the enlargement of the back-arc domains, drastic thinning of the overriding crust and underlying asthenospheric upwelling that triggered partial melting of a depleted mantle (Agostini et al., 2007; Menant et al., 2016a). This coeval magmatic evolution across the whole Mediterranean domain reinforces the similar timing noted above in terms of deformation and calls for a similar evolution in the mantle below the Mediterranean. It is not clear whether the progressive formation of back-arc domains alone can explain this evolution in the nature of magmas or an additional influence of mantle plumes is required (Duggen et al., 2009; Facenna and Becker, 2010). As proposed by Facenna et al. (2013b) the magmatism of Turkey after 10 Ma is strongly influenced by material of the Afar plume that migrated from south to north after the Africa-Eurasia collision at ~30 Ma. Similarly Duggen et al. (2009) proposed that a sub-lithospheric corridor has conveyed the hot material of the Canary plume northward until the Western Mediterranean. Both the intrinsic evolution of the subduction zone and the influx of plume material in the Mediterranean realm may have contributed to the observed evolution.

7 Discussion

We now critically discuss the implications of these reconstructions. We start with their reliability and put the emphasis on observations that are not explained by this kinematic model. We then discuss the consequences of the proposed kinematics in terms of driving forces before discussing the rheological implications in the upper and the lower plates. The initial configuration of the subduction zones 35 Ma ago and their polarity is then discussed and compared to other published situations. The transition from the formation of mountain belts to back-arc extension and the end of the HP-LT metamorphism are then summarized and discussed. Finally, the geometry and kinematic evolution of transfer zones in the Western Mediterranean is studied.

7.1 Reliability of reconstructions

Our reconstructions are purely based upon kinematic parameters derived from independent geological data sets and independent from any pre-conceived model (Fig. 3; Supplementary Material #1). Rates of shortening in mountain belts, rates of extension in rifted areas, the timing of shortening or extension, palaeomagnetic rotations, ages of magmatic or metamorphic events are indeed all independent from each other. They were taken from the vast corpus of literature available on this region in papers that were not dealing with large-scale geodynamic models. The resulting model is thus independent from our prejudice on the important role played by slab retreat in the dynamics of this fast deforming region. Then, the data gathered in the literature come with some errors that are difficult to estimate. Managing several hundred features in GPlates is complex and entering error bars on each data would have rendered the task impossible. The general picture is however not so different to the first order from other less detailed reconstructions such as those proposed by Rosenbaum et al. (2002) for instance, with however more details in the configuration of subduction zones. The novelty of the model also lies in the unprecedented details of the tectonic history decorating the reconstructions and of the motion paths that brings new insights on the kinematic evolution of the region since the late Eocene. The integration of the Western Mediterranean within the whole Mediterranean realm is also an originality of the model and provides an alternative vision to van Hinsbergen et al. (2019), reconciling the tectonic history of this region with its magmatic and metamorphic evolution. Different choices in the vast geological data base of this region would probably lead to slightly different reconstructions, but we are confident that the first-order picture would remain the same. Compared to the reconstructions proposed by Schettino and Turco (2006), our starting hypotheses are entirely different as we do not use any information from magnetic anomalies in the back-arc basins and our blocks are deformable, not rigid. Using magnetic anomalies is the most reliable way of reconstructing the past plate kinematics, but in the Western Mediterranean these anomalies are not clearly identified and some of the postulated oceanic crust was shown to be exhumed mantle instead; the justification of this approach is thus questionable.

Despite the errors inherent to the nature of the geological data we used, we think our reconstruction model is solid, but some special consideration should however be focused on the tectonic evolution of the Balearic islands that is not easily explained. If the middle Miocene compressional event recorded on Ibiza and Mallorca can be understood as a consequence of the docking of the AlKaPeCa block with the north African margin (Etcheve et al., 2016), neither northward-migrating shortening observed on Mallorca from the late Oligocene to the Langhian (Sábat et al., 2011) nor its different timing in Ibiza and Majorca are explained. Why should the Balearic islands be under compression while the surrounding basins are extending is a difficult and debated question that should be addressed in future works and this is a limitation of our model.

The reconstructions of the Alboran domain are also likely to be debated because of the lack of information on the finite amount of retreat of the subduction below Gibraltar as already mentioned above. In our reconstructions we move the trench eastward back in time – so that the Alboran crust returns to the thickness of an orogen of about 40 km but an alternative choice of a thicker crust would make the retreat larger. This is another weak point of our reconstructions. A similar problem arises for the pre-rift reconstruction of the Gulf of Lion margin. We assume that the crust had a normal thickness of about 30 km before rifting started using the restoration of Jolivet et al. (2015a, 2015b). One could instead assume a larger thickness and thus obtain a tighter fit of the Corsica-Sardinia block along the Provence margin. At the scale of the whole Western Mediterranean it would not change much the general picture but it would modify the pre-rift geometry at the scale of the Pyrenees-Gulf of Lion transition. Another debated point is the
age of the HP-LT parageneses in the Internal Zones of the Betics, and more specifically the Nevado-Filábride Complex. We have deliberately chosen to set the peak of pressure in the eclogite-facies in the Eocene, following the results obtained by Augier et al. (2005a) and Li and Massonme (2018), rather than the middle Miocene ages obtained by López Sánchez-Vizcaino et al. (2001) and Platt et al. (2006), as discussed earlier in the paper. This choice has implications on the geometry and kinematics of the Alboran domain accretionary wedge.

7.2 Kinematics in various frameworks and driving forces

In order to discuss the various possible drivers of the observed kinematics and deformation, in the western and central Mediterranean region, we plot motion paths from our reconstruction model in three different kinematic frameworks, using a facility of GPlates (Fig. 7). The three frameworks are with (1) Eurasia fixed, (2) Africa fixed and (3) the hot spots framework (Seton et al., 2012; Nirengarten, 2016; Nirengarten et al., 2018).

The finite amount of slab retreat in our reconstructions comes with large uncertainties, especially for the western margin of the AlKaPeCa block. The amount of retreat of Gibraltar subduction zone is obtained using the amount of shortening within the Betic-Rif orogen (Crespo-Blanc et al., 2016), the amount of extension in large MCCs such as the Sierra Nevada-Sierra de los Filabres, the assumption of a normal initial crustal thickness (~30 km) in the future Alboran Sea and the width of the oceanic crust in the Algerian Basin. Using a thicker crust before back-arc rifting would end up with a larger finite displacement of the Alboran block. Our reconstructions thus predict a minimum westward displacement of about 400 km of the Gibraltar arc. The present-day position of the subduction front is further to the west but it corresponds to the front of the sedimentary wedge built at the expense of sediments deposited on the Atlantic oceanic crust, not to the front of the Alboran domain and is thus not indicative of the amount of retreat. A recent study of the East Algerian basin (Driussi et al., 2015), south of the Balearic islands, suggests that the oceanic crust in the basin was emplaced in two steps: a first period with NW-SE extension and SE-ward slab retreat and then E-W extension and westward slab retreat. Depending upon the respective widths of the oceanic domains opened during these two stages, the finite westward displacement of the subduction zone below the western margin of the Alboran block will be different. Maximizing the westward displacement would place the initial position of the trench farther to the northeast, an option chosen for instance by van Hinsbergen et al. (2014). Our reconstruction shows a minimum amount of retreat instead, but larger values cannot be ruled out.

Note that some motion paths do not span the entire time frame of 35 Ma because they denote the displacements of features that did not exist in the earliest stages. Because the different features may belong to blocks that have totally different kinematic histories, some motion paths may cross each other, which may look odd. For instance, features belonging to the Apulian block since the earliest stages first follow the motion of Africa before they are caught in the eastward motion due to back-arc extension in the Tyrrhenian Sea. The motion path of such features can then be crossed by the path followed by more internal blocks belonging to the AlKaPeCa block and moving faster during the opening of the southern Tyrrhenian Sea and they are thus not at the same place at the same period. A more detailed explanation is provided in Supplementary Material #3.

These motion paths representing the kinematics within the crust are then compared to the fabrics of the underlying asthenosphere through SKS-wave anisotropy taken from Faccenna et al. (2014) and references therein, including Diaz et al. (2015) and Salimbene et al. (2013). A more recent compilation for the Alps and North Adriatic region can be found in Salimbene et al. (2018). We here assume that this anisotropy represents the flux in the asthenosphere beneath this region, or the shearing direction between the flowing asthenosphere and the rigid lithosphere (Barruol et al., 2004; Lucente et al., 2006; Buontempo et al., 2008; Jolivet et al., 2009). This observation is also in line with the conclusion of a shear-wave tomography model suggesting an eastward flow of asthenospheric mantle underneath the western Mediterranean back-arc basins (Panza et al., 2007)

As shown in Jolivet et al. (2009), the inferred mantle flow below the back-arc domain fits the trend of stretching lineations in exhumed metamorphic core complexes where the deformation in the middle and lower crust can be observed. A swing in the fast direction of the anisotropy is observed from the northern Tyrrhenian Sea (E-W) to the Apennines (N-S), with SKS anisotropy perpendicular to the strike of the arc in the back-arc region and parallel to the arc closer to the trench, a situation that is observed in young orogens (Meissner et al., 2002). Here we see that the motion paths in the Eurasia-fixed framework also show a good fit with the fast direction of the anisotropy in the mantle in back-arc regions, for instance in the northern Tyrrhenian Sea, in Corsica and also in the Internal Betics. The direction of the motion paths is the same in the back-arc region and in the mountain belts and it is parallel to both back-arc extension and shortening in the belt. The motion path are thus perpendicular to the seismic anisotropy that is parallel to the Apennines or the Gibraltar arc (Jolivet et al., 2009).

From the comparison of these two different proxies (mantle fabrics and crustal flow) two main conclusions can be reached. (1) the best fit is obtained with the Eurasia-fixed framework and (2) the crustal flow due to slab retreat toward the east or the west dominates the regional kinematics. It is dominant over the absolute motion of Africa and Eurasia in the hot spots framework. It is best expressed by the eastward motion of Calabria (~800 km) (Figs. 7 and 8) that is almost similar in all three frameworks, also on the Gibraltar side where the absolute motion paths are clearly deviated by back-arc opening of the Alboran Sea (~400 km, which is a minimum estimate). In the southern Tyrrhenian Sea the earliest part of the motion path (before 15 Ma) are not aligned with mantle fabric. This is because the southern Tyrrhenian back-arc opening only started at 15–10 Ma. As discussed by Jolivet et al. (2009) the mantle fabric can be totally reset in less than 10 Ma and only the recent part of the motion path should be considered for comparison.
Fig. 7. Motion paths calculated from the reconstructions in three different kinematic frameworks. Upper: stable Eurasia; Middle: stable Africa, Lower: absolute motion (Atlantic-Indian hot-spots). Grey bars: fast polarization directions of SKS-waves (Faccenna et al., 2014; Díaz et al., 2015).
The best fit of mantle fabric and crustal kinematics obtained within the Eurasia-fixed framework suggests that mantle flow due to slab retreat, modulated by slab tearing and slab detachment, is the dominant driver of the deformation in Mediterranean back-arc regions, as commonly proposed (Wortel and Spakman, 1992; Carminati et al., 1998a, 1998b; Jolivet and Faccenna, 2000; Wortel and Spakman, 2000; Faccenna et al., 2001a, 2001b, 2004; Jolivet et al., 2009; Faccenna and Becker, 2010; van Hinsbergen et al., 2014). The asthenospheric flow induced by slab retreat underneath the overriding plate moreover creates a component of shear at the base of the lithosphere that further controls the deformation in the back-arc region (Jolivet et al., 2009, 2015a, 2015b, 2019; Sternai et al., 2014). The poorer correlation of the motion paths in the hot-spots reference frame with the seismic anisotropy shows that absolute motion of the African and Eurasian plates is not the dominant process creating the mantle fabric here. Slab retreat is instead the first-order driver. This interpretation is well in line with recent numerical modelling of the interaction between surface kinematics and mantle convection showing that plate attached to a subducting slab are driven by slab pull and plates not attached to a subducting slab are mostly driven by the flow of mantle underneath (Coltice et al., 2019).

In this school of thought, slab dynamics is the main driver of plate deformation in back-arc regions, but other models have been proposed. In a recent paper, Mantovani et al. (2020), after Mantovani et al. (2009), discuss the geological features of the Western Mediterranean and favor an alternative mechanism involving mostly extrusion driven by the African-Eurasia convergence. This model is partly similar to early models proposed by McKenzie (1972, 1978) and Tapponnier (1977). It was also proposed to explain the deformation of south-east Asia as a consequence of the northward indentation of India into Asia (Tapponnier et al., 1982). Extrusion models however involve large-scale strike-slip fault systems, such as the Red-River Shear Zone or the North Anatolian Fault, linking the region of crustal thickening in the collision zone and the back-arc domain outside the collision zone. No such fault is
observed in the Western Mediterranean region and one does not find either the equivalent of the Tibetan plateau or the Anatolian plateau there. A second objection to this type of model is that it can hardly explain the observed extension at the leading edge of the extruded system at variance with models involving slab retreat such as Sternai et al. (2014) and Capitanio (2014). Further numerical studies should focus on the respective merits of both classes of models. A third objection is the observed velocities in back-arc regions on the Western Mediterranean which are much higher than the velocity of Africa-Eurasia convergence. We thus think that the domination of eastward and westward kinematics over the absolute kinematics is a consequence of the high velocity of slab retreat that amounts to more than 10 cm/yr, up to 19 cm/yr according to Nicolosi et al. (2012), especially in the South Tyrrhenian region, in comparison to the slower absolute motion of Africa and Eurasia about 1 cm/yr (Macchiavelli et al., 2017).

7.3 Nature of the subducting lithosphere

In our reconstructions, we show a partly oceanic connection through en-échelon basins controlled by left-lateral transform faults in the narrow space between African and Iberia, never wider than 200–300 km, between the Mediterranean domain and the Atlantic. The nature of crust flooring the basin is in fact not precisely known. All recent reconstructions in the Mesozoic indeed consider a segmented domain along NW-SE trending transform faults accommodating the oblique Africa-Eurasia motion. Schettino and Turco (2009) show a fully oceanized domain while Fernández et al. (2019) show a more detailed picture including exhumed mantle along the ocean-continent transitions in between the transform faults. Leprêtre et al. (2018) and Gimeno-Vives et al. (2019) show a partly oceanized domain with exhumed mantle. We have followed these recent interpretations in the reconstructed maps.

There was for sure a marine domain where platform sediments were deposited in the Mesozoic before the beginning of shortening in the Late Cretaceous, but no evidence of true ophiolites that would testify for a large open ocean has ever been found. The only tectonic unit that could call for an oceanic environment is the Bédar-Macael Unit at the top of the Nevada-Filabride complex where metasediments and ultramafic rocks show evidence of HP-LT metamorphism in the eclogite facies during the Eocene (Puga et al., 2000, 2002, 2017; Augier et al., 2005a, 2005b, 2005c, 2005d; Li and Massonne, 2018). The so-called Cobdar Ocean (Cb. O. in Fig. 5A) could have been a small ocean or a hyper-extended continent-ocean transition that could also include farther west the Ronda and Beni Bousera peridotite as proposed by van Hinsbergen et al. (2014) and Bessière (2019). Its exact width and position before the formation of the nappe stack is, however, difficult to assess. Our best guess is that it was located to the north of the AlKaPeCa terranes and was integrated in the accretionary wedge by a southward subduction during the Eocene, like in Chalouan and Michard (2004). Otherwise, all tectonic units involved in the Betic-Rif accretionary wedge are of continental origin, probably parts of a thinned continental domain located between Africa and Iberia that was progressively incorporated in the Betic-Rif accretionary wedge during the westward migration of the arc. It could be indeed argued instead that the true oceanic domain has been totally subducted and that no remains can be found within the orogen and we cannot totally exclude this possibility (see Vergés and Fernández, 2012).

Further to the east and northeast, in the Apennine-Calabria subduction zone, the subducting lithosphere is more likely to be truly oceanic for two main reasons. First, a calc-alkaline magmatic arc has developed above the subduction zone in Sardinia and Provence from 32 Ma, suggesting the classic subduction of an oceanic domain. The second reason is that the slab now seen in tomographic models below the Tyrrenhian Sea was dense enough to induce a fast retreat, which is less likely with a continental lithosphere.

7.4 thick, hot and weak crust in the upper plate

Post-dating Late Cretaceous-Eocene mountain building, from Corsica to the Betic-Rif orogen, rifting in back-arc regions of the Western Mediterranean, like in the Eastern Mediterranean, leads to the formation of MCCs, topped with low-angle normal faults and ductile shear zones, and in some cases intrusions of granitoids involving a significant component of crustal melt (Daniel and Jolivet, 1995; Westerman et al., 2004; Farina et al., 2010). Thickened in the preceding stage, the lower continental crust was thus warm and weak when extension started. In the Tuscan archipelago, the Monte Capanne and Porto Azurro plutons of Elba Island (Figs. 4B and 5F) were exhumed below east-dipping low-angle detachments (Keller and Pialli, 1990; Daniel and Jolivet, 1995; Jolivet et al., 1998; Collettini and Holdsworth, 2004; Westerman et al., 2004). The Betic Cordillera provides the example of the Sierra Nevada-Sierra de Los Filabres and Sierra Alhamilla MCCs characterized by HP-LT followed by HT-LP metamorphic (amphibolite-facies) metamorphism exhumed below the top-to-the west Filabres low-angle detachment (Jabaloy el et al., 1993; Augier et al., 2005c). In the Gulf of Lion, the distal part of the margin has been interpreted as a MCC made of exhumed lower crust at the time of rifting below a north-dipping detachment (Jolivet et al., 2015a, 2019). A conspicuous sub-aerial erosion surface at the top of this MCC shows that this rifting stage was accommodated with a shallow basin or even emerged crust (Jolivet et al., 2015a), while the transition zone toward the Valencia Basin shows a boudinage of the lower crust and low-angle ductile shear zones (Maillard et al., 2020). This region is also characterized by intense volcanism and magmatic underplating during rifting both on land (Sardinia) (Casula et al., 2001; Lustrino et al., 2009) and offshore (Eastern Valencia Basin) (Maillard and Mauffret, 1999; Maillard et al., 2020). While most of the crustal thinning observed in the southwestern part of the Valencia basin dates back to pre-Albian times (Ethève et al., 2018), the northeastern part of the basin instead shows evidence for Oligocene rifting (Maillard et al., 2020). All these observations show that the crust was weak and hot in the overriding plate over the eastern Pyrenees, the future Gulf of Lion and eastern Valencia basin, which appears crucial for transmitting shear stress from the flowing asthenosphere to the lower crust and for explaining the similar mantle and deformation pattern in these warm regions (Fig. 7;
see also discussion in Sections 7.2 and 7.6) (Jolivet et al., 2018, 2019). Three reasons explain this weakness: previous crustal thickening, intense magmatism and the presence of the asthenosphere at low depth during slab retreat and tearing.

### 7.5 Subduction polarity

In opposition to most classical models, Vergés and Fernández (2012) (Fig. 1B) proposed that the slab now observed below the Gibraltar arc and southern Iberia evolved from the southeast-dipping subduction below the Alboran domain, separated from the main northwest-dipping subduction of the Ionian Sea further east by a NW-SE transform fault. Other models favor a single northwestern subduction that has acquired the observed strong curvature during retreat (Lonergan and White, 1997; Lacombe and Jolivet, 2005; van Hinsbergen et al., 2014) or two facing subductions and much less westward retreat (Michard et al., 2002; Chalouan and Michard, 2004; Leprêtre et al., 2018). Our reconstructions do not show a continuous simple northward subduction and, instead, favor a situation partly similar to Michard et al. (2002) on the one hand, and Vergés and Fernández (2012) on the other hand. Reconstructing the position of the trench without any a priori model leads to a situation at ~35 Ma where the future Gibraltar subduction is oriented N-S and extends eastward within a southeastward dipping trench where the so-called Cobdar Ocean is consumed. A significant difference with Vergés and Fernández (2012) is however that the upper plate of the south-dipping subduction is the AlKaPeCa block and not Africa. This situation is more similar to the proposition of Chalouan and Michard (2004) and Leprêtre et al. (2018) than van Hinsbergen et al. (2014) and it does not involve the transform fault postulated by Vergés and Fernández (2012) to accommodate the opposite dips of the two subduction zones, a structure that is not expressed in the local geology. Subduction below the two sides of the AlKaPeCa blocks solves this problem.

The motion paths (Fig. 7) show that the displacements with respect to Africa are almost parallel to the North African margin with very little convergence, and slightly oblique to the south Iberian margin with a minor amount of convergence. Most of the displacement is accommodated across the N-S trending subduction zone to the west. This situation is due to the option we have chosen for closing back the Algerian basin and the Alboran Basin. Had we instead chosen the van Hinsbergen et al.’s (2014) solution we would have had to consume most of the subducted lithosphere across the north-dipping subduction, progressively retreating toward the southwest. The solution of van Hinsbergen et al. (2014) is mainly inspired by a numerical model of a retreating slab leading to a final geometry similar to the observed one. Chertova et al. (2014) indeed test different models of evolution of the Western Mediterranean with 3-D numerical experiments. They conclude that the best fit of the present-day geometry of the imaged slab is obtained with an initial short northwestern subduction south of the Balearic Islands compared to models with a continuous subduction from Gibraltar to the Balearic or initial subduction underneath the African margin. A strong rotation of the slab, more than 180°, is observed with this model. The model also fits several time constraints such as the timing of docking of the AlKaPeCa blocks with the northern margin of Africa. In this study, we worked totally independently of any a priori model and our reconstruction does not lead to more than 400 km of slab retreat. The van Hinsbergen et al.’s solution remains possible because some of the shortening might have been accommodated in now subducted units. With the option we chose for reconstructing the Alboran domain, which minimizes its displacement, we end up with a situation intermediate between that of Vergés and Fernández (2012) and Chalouan and Michard (2004).

### 7.6 From shortening to extension in the overriding plate

The reconstructions highlight a 3-D complexity at the junction of the Pyrenees and the Gulf of Lion. The present-day Pyrenean Belt ends abruptly to the east where they give way to the rifted margin of the Gulf of Lion (Réalhaut et al., 1984; Mauffret et al., 1995; Séranne, 1999; Jolivet et al., 2015a, 2015b, 2019; Chevrot et al., 2018). Rifting starts at about 32 Ma, which is coeval with an uplift and exhumation episode in the Axial Zone of the Eastern Pyrenees (Gorini et al., 1993; Gorini et al., 1994; Fitzgerald et al., 1999; Jolivet et al., 2015a), as expected on the shoulder of a rift. However, shortening continues in the western part of the Pyrenees where south-vergent thrust faults are still active until the Early Miocene (Murioz, 2002; Jolivet et al., 2007; Labaune et al., 2016). This 3-D pattern is complex and the geometry of the stress field not easy to understand. Why does compression continue during ~10 Ma in the west, while extension is well underway in the nearby Gulf of Lion and in the Valencia Basin?

Nevertheless, apart from limited on-going southward thrusting in the west, the main shortening across the Pyrenees ends approximately when the subduction regime changes in the whole Mediterranean, from compressional to extensional, in the late Eocene to Oligocene. Whether compressional stresses are still transmitted from Africa to Europe through the Pyrenees west of the extending domain is an open question. The Pyrenees end along the Mediterranean coastline and seismic data show the progressive crustal thinning from the mountain belt to the Gulf of Lion passive margin (Chevrot et al., 2018; Diaz et al., 2018). The first extensional features seen in the eastern Pyrenees consist of minor high-angle normal faults with a strike-slip component and the motion along these faults controlling the Cerdanya half-graben dates back to the Middle Miocene, thus posterior to rifting in the Gulf of Lion (Pous et al., 1986; Cabrera et al., 1988; Gabas et al., 2016). The Catalan-Baleares Transfer fault can kinematically accommodate the transition from shortening to extension, but the distribution of stresses is complex. Nevertheless, it remains that the main Pyrenean shortening ceased progressively when slab retreat started, between 32 and 20 Ma and that the Pyrenees were fast brought down to sea level and then submerged in the east to be replaced by the Gulf of Lion passive margin (Jolivet et al., 2020). 20 Ma is also the period of the last shortening event along the southern Pyrenean thrust front. One reason could be the change from southeastward to westward slab retreat in the Alboran region that...
deviated the mantle flow underneath in an E-W direction, precluding the transmission of N-S compressional stresses.

In the meantime, Africa-Eurasia convergence was active all along and its effects were felt again only once the Gibraltar slab had retreated westward far enough in the Alboran region (Jolivet et al., 2006; Spakman et al., 2018). Some compression was felt within the African plate during the Oligocene and Miocene south of the Atlas (Téson et al., 2010), but the main stages of construction of the Atlas are recorded in the Eocene and the Pliocene (Fritzé de Lamotte et al., 2000; Lanari et al., 2020a, 2020b). One simple explanation is that the fast retreat was diverting the mantle flow toward the west, as is also suggested nowadays from SKS-wave anisotropy below Iberia (Fig. 7) further suggesting that mantle flow underneath plays a key-role in driving crustal deformation, at least in regions where the crust is warm and weak (Jolivet et al., 2009, 2018; Sternaï et al., 2014; Menant et al., 2016b). The interaction of the dipping slab with the mantle flow driving the absolute northeastward motion of Africa and Eurasia may play an active role in the present-day stress regime (Spakman et al., 2018) but the Pliocene resumption of compression in the High-Atlas (Fritzé de Lamotte et al., 2011) and the recent NNE-SSE compression recorded all across France (Bergerat, 1987; Cornet and Burlet, 1992; Baize et al., 2013) as well as the NWW-SSE trending $\sigma_{hmax}$ within Iberia in an extension or strike-slip regime (de Vicente et al., 2008) suggest that a large-scale engine should be looked for involving the relative motion of Africa, Asia and North America as well as the mantle flow underneath.

7.7 Coeval end of HP-LT metamorphic conditions

Our reconstructions go back to the Late Eocene, which corresponds to the end of HP-LT metamorphic conditions in the studied region. Ages of the HP-LT metamorphism in the Betics (Alpujárrides and Nevado-Filábrides) are debated but Eocene ages are likely (Augier et al., 2005a; Platt et al., 2005; Li and Massonne, 2018). In addition, a recent dating campaign in the Alpujárrides in the eastern and central Betics (Bessière, 2019) shows that the peak of metamorphism dates back to $\sim 38$ Ma. We thus consider here that the middle Miocene ages obtained in the Nevado-Filábride complex (López Sánchez-Vizcaíno et al., 2001; Platt et al., 2006) are representative of the exhumation of this complex, not of the peak of pressure; for a detailed discussion of published radiochronological data, see Bessière (2019). Alpine Corsica, the Alps or Calabria show coeval peak metamorphism ages within errors, very close to the major change from shortening to extension in the overriding plate. The case is very clear in Alpine Corsica where the 34 Ma age is within error similar to the age of the first extension along the East Tenda Shear Zone (Brunet et al., 2000). In the Dora Maira massif of the Western Alps, the youngest published ages of the UHP metamorphism are also around 33–35 Ma (Duchêne et al., 1997; Rubatto et al., 1997; Rubatto and Hermann, 2001; Schertl and Hammerschmidt, 2016), which is almost the same as the age of the flysch-to-molasse transition in the western Alps and the westward propagation of the thrust front (Vignaroli et al., 2008, 2009). In the Edough Massif, NE Algeria, the 32 Ma age of rutilte is thought to be close to the age of peak pressure conditions (Bruguier et al., 2017). Without evidence for UHP metamorphism, the alpine metamorphic units of Calabria also yield peak metamorphism ages between 33 and 38 Ma before overprinting with extensional retrograde deformation (Rossetti et al., 2004). It thus appears that everywhere along the future Apennines subduction zone as well as in the Alps, available ages of the last HP-LT metamorphism are close to the age of the first back-arc rifting nearby.

We interpret this situation by considering that these ages represent the last moment when exhumed tectonic units reached the maximum depth within the subduction zone and started their exhumation because the subduction regime had changed. Because of slab retreat, the subduction channel opened and accreted units were soon exhumed. Slab retreat facilitates exhumation of HP-LT tectonic units, as shown by the case of the Cycladic Blueschists or the Phylite-Quartzite Nappe in the Aegean region (Jolivet et al., 1994, 2003; Brun and Faccenna, 2008; Jolivet and Brun, 2010). In the case of the Western Alps, the coeval fast exhumation of the UHP units and westward propagation of the thrust front could also be a consequence of the inception of slab retreat in the Apennines subduction zone and induced opening of the subduction channel below the Alps, as initially proposed by Vignaroli et al. (2008). A significant difference however appears between the Western and Eastern Mediterranean. In the west, there is almost no HP-LT metamorphic units yielding ages younger than 30 Ma, the island of Gorgona in the Northern Tyrrhenian Sea and the MCCs of Tuscany (Brunet et al., 2000) with ages around 25 Ma being exceptions. In the Eastern Mediterranean instead, blueschist exhumation lasted until about 16–15 Ma in Crete and the Peloponnese (Jolivet et al., 1996, 2010), despite active back-arc extension since about 30 Ma. This difference might be due to the presence of a wide oceanic domain not yet subducted south of Crete in the Miocene, whereas the Calabrian arc is much narrower. This would allow slab retreat to continue in the Eastern Mediterranean region associated with protracted basal accretion and exhumation of HP-LT metamorphic units until more recent periods.

7.8 Slab tearing, transfer zones and back-arc kinematics

We now focus on the pre-8 Ma period, before the change toward the resumption of compression, progressively generalized to the whole Western and Central Mediterranean. The total displacements of the Calabria and Gibraltar arc since 35 Ma are respectively 800 and 400 km, the latter value being a minimum (Fig. 8). These large displacements of the retreating slabs imply similar displacement of the mantle below the overriding plate, which implies long-distance effects of the retreat, which is well shown by seismic anisotropy (Barruol and Granet, 2002; Lucente et al., 2006; Jolivet et al., 2009; Salimbene et al., 2018). The eastward mantle flow related to this slab retreat is indeed felt as far as the Alps and the Pyrenees (Fig. 7). The fast direction of seismic anisotropy showing the toroidal asthenospheric flow around the Alpine arc gets parallel to the fast direction under Provence and the Pyrenees, which is in turn
parallel to the main direction of slab retreat on the map showing motion paths in the Eurasia-fixed framework.

The displacement field shows, however, discontinuities bounding four kinematically different domains (domains A, B, C and D in Fig. 9). Some are sharp like between domains B and C or north and south of domain D, other are more diffuse like between domains A and B. These discontinuities result from the independent behavior of torn slab pieces during retreat. The structures accommodating these differential movements in the overriding lithosphere (transfer zones) are variable from one place to another. The sharpest and largest of these transfer zones is between domains B and C. It runs from the western margin of the Gulf of Lion all the way to the northern margin of Sicily (Catalan-Baleares-Sicily Transfer Zone, CBSTZ in Fig. 9), with a strike changing following the small circles of the rotation of Corsica and Sardinia. Its northern part corresponds to a series of NNW-SSE-striking dextral transfer faults, the geometry of which is now well described based on the interpretation of seismic lines in the Gulf of Lion and Valencia Basin (Maillard et al., 2020). The Catalan transfer Fault runs along the western margin of the Gulf of Lion and the eastern coastline of the Pyrenees. It was initially placed here for kinematic compatibility but was not clearly identified as such. A recent study (Canva et al., 2020) shows that it is associated with a prominent NNW-SSE-striking magnetic anomaly interpreted as underplated gabbroic rocks. The North Balearic Fracture Zone is found further south. The fracture zone are well imaged in seismic profiles crossing the transition between the Valencia Basin and the Gulf of Lion and is associated with syn-rift basins and lower crustal domes (Maillard et al., 2020). The relative motion across the CBSTZ is however not purely strike-slip. Motion paths in the Eurasia-fixed or Africa-fixed frameworks show a divergence southwest of Sardinia, implying a component of extension perpendicular to the transfer zone. This extension component could explain the fan-shaped pattern of oceanic magnetic anomalies in this region, i.e. the Hamilcar anomalies of Mauffret et al. (2004).

The transfer zone between Domains B and A is diffuse and does not correspond to any specific strike-slip fault. It is rather the limit between the northern and southern Tyrrenhian seas with a transition from upper crustal blocks in the north to highly thinned continental crust and exhumed mantle to the

Fig. 9. Different kinematic domains and transfer zones (thick grey lines) discussed in the text. CBSTZ: Catalan-Baleares-Sicily Transfer Zone. Large blue arrows show the average direction of displacement between the main transfer zones.
south (Prada et al., 2014, 2018). The transfer zone between domain C and D is also diffuse, but Strzrezynski et al. (2010) have identified a large dextral discontinuity oriented N120°E limiting the Internal Kabylides to the west. It has been active between the Eocene and ∼19 Ma, just before the main change in the direction of slab retreat from southward to westward. They also propose that similar structures do exist and have accommodated the opening of the Algerian Basin.

The northern and southern limits of domain D (the Alboran Sea) are more clearly identified. The southern limit corresponds to the northern steep Morrocan margin, reworked by compression in the recent period. The trajectories with fixed Africa show that the motion is oblique on the margin with a component of thrusting and a component of left-lateral shear with respect to the direction of the western north African margin (Fig. 7, 2nd panel). Several left-lateral faults (Nekor Fault, Jebha Fault) and the thrust contacts within the Rif have accommodated this differential movement (Lafosse et al., 2018). The northern transfer zone corresponds to the Betics. Between 20 and 8 Ma the displacement has been mostly from east to west in the Betics with the exhumation of the Sierra Nevada-Sierra de los Filabres MCC, the Sierra Alhamilla MCC and some dextral strike-slip faults, plus a component of northward thrusting in the north (Platt and Vissers, 1989; Vissers et al., 1995; Augier et al., 2005c, 2013; Jolivet et al., 2006, 2008; Martinez-Martinez et al., 2006; Frasca et al., 2015). The two MCC are elongated parallel to the direction of shearing, making them a-type domes in the sense of Jolivet et al. (2004). As shown by Le Pourhiet et al. (2012) such domes can form in an extensional context with a significant strike-slip component. Similar domes are found in the center and east of the Aegean Sea in the wide transfer zone above a major tear in the Hellenic slab (Jolivet et al., 2015b).

The reaction of the crust in the overriding plate above slab tears is thus variable, with either localized strike-slip faults with some extensional component, deep intrusions and crustal domes, or with mainly a-type crustal domes oriented parallel to the tear fault, with a different expression in the brittle and lower crusts. Other examples show less localized structures that remain to be clearly identified.

The origin of the tear faults (in the subducting plate) is quite obvious in some cases, much less in others. The main tear below the CBFSZ can have originated along the ocean-continent transition south of Apulia (Figs 5A and 9) but this is highly debatable as the geometry of the Apulian block is poorly known. The earliest evidence for a tear in this region is found in Provence where adakitic magmatism is found in the Late Eocene (Réhault et al., 2012) (Fig. 4). The transition between the Pyrenees and the Gulf of Lion is approximately located south of the left-lateral bend between the northern thrust front of the Pyrenees and Provence. Although the strike of the thrust front along this bend is slightly different from the strike of the transfer zone, it is possible that this bend corresponds to a transfer zone active during Pyrenean shortening (Séranne, 1999), which would have been reactivated during subsequent back-arc rifting. The tear faults on either side of the Alboran Sea are easier to understand as they correspond to the limits of the oceanic or thinned continental domain between Iberia and Africa. The transfer zone between domain C and D could originally be one of the transform faults in the Tethyan oceanic domain that are thought to display a similar orientation as in Vergés and Fernández (2012) and Lepêtre et al. (2018).

In view of our reconstructions, it also appears that the spatial and temporal distribution of magmatism is in part controlled by slab retreat, tearing and transfer zones. Thus, the CBSTZ has localized magmatism since its initiation in the Oligocene and early Miocene (Canva et al., 2020; Maillard et al., 2020) until the recent development of offshore magmatism north of Sicily (Fig. 4) (Cocchi et al., 2009). Figure 4 shows the distribution of magmatism in this region from the first adakites in the late Eocene to the Oligocene and early Miocene magmatism underplated below the Catala transfer zone as well as the syn-rift magmatism of the northeastern Valencia basin along transfer zones. Transfer zones within the Valencia trough are indeed associated with magmatic venues (Maillard and Mauffret, 1999; Maillard et al., 2020). The southeast extremity of the CBTSZ, north of Sicily, is spatially correlated with the recent emplacement of K- and Na-alkaline igneous rocks, above a slab tear and associated reorganization of mantle flow around the edges of the remaining piece of slab (Faccenna et al., 2005). In addition, the westward and eastward migration of magmatism along the northern margin of Africa is related to the progressive pealing of the torn African lithospheric mantle during its retreat (Maury et al., 2000). A similar timing, distribution and composition of magmatic products has also been reported further east in the Western Anatolia-Eastern Aegean domain during the middle Miocene (Fig. 4), related to a major slab tearing event occurring coevally underneath (Dilek and Altunkaynak, 2009; Menant et al., 2016a, 2016b).

The change from N-S to E-W extension in the Betics occurred some 20 Ma ago (Crespo-Blanc et al., 1994; Crespo-Blanc, 1995; Azañón et al., 1997; Jolivet et al., 2006). A similar change happened approximately at 15–20 Ma north of the CBSTZ as shown by the kinematic trajectories, at the approximate time when the AlKPaPeCa units collided with the northern margin of Africa (Figs. 5D and 5E). In different reconstructions it happens as soon as 20–25 Ma (Lepître et al., 2018) but the exact age of docking is difficult to assess precisely because the original outboard the Africa is now buried below the orogen. Considering an age of ∼20 Ma for the docking would make it coeval with the change in the direction of extension and thus of the direction of slab retreat from N-S to E-W in the Betics. It can be proposed that it is precisely the docking on the African margin that led to tearing the subducting plate in two main pieces on either side of eastern Algeria where the oldest magmatic rocks are observed along the North African coast, one retreating eastward and one retreating westward. This scenario is compatible with the migration of magmatism from east to west along the northern margin of Africa between 20 and 9 Ma (Fig. 4) (Maury et al., 2000; Coulon et al., 2002). The transition through time from oceanic to continental subduction in the central part of the system at around 4°E would trigger a detachment of the slab there, which would then propagate eastward and westward.

8 Conclusions

Detailed reconstructions of the Western Mediterranean from 35 Ma to the Present are presented, based on geological...
constraints in mountain belts and extended domains, as well as paleomagnetic and P-T-t constraints. Once integrated within the entire Mediterranean realm, extracted paleo-tectonic maps and reconstructed cross-sections provide an unprecedented precise framework for discussing the interactions between retreating subducting slabs and the overriding plate in a confined environment.

One of the initial questions was the configuration of subduction zones before the inception of slab retreat. The backward step-by-step reconstruction leads to a model where two subduction zones are active. One subduction proceeds toward the NW below the Balcaces, Corsica and Sardinia and one toward the east or southeast below the Alboran block. This configuration is intermediate between the options proposed by Michard et al. (2002) and Vergès and Fernández (2012).

The comparison of motion paths extracted from the reconstruction model shows a good fit with the fast polarization directions of SKS-waves in the Eurasia-fixed framework, suggesting that the main driver of crustal deformation between 35 and 8 Ma is the retreat of slabs eastward and westward and the associated asthenospheric flow, as the velocities of crustal blocks following the retreat are much larger than the motion of Africa with respect to Eurasia at the limits of the deforming area. The main direction of retreat was N-S or NW-SE until the AlKapCa blocks docked against the northern margin of Africa around 20 Ma. The subsequent subduction of continental lithosphere then initiated a detachment of the slab that propagated as tears toward the west and east along the northern margin of Africa, inducing a change in the direction of extension, then mostly E-W. Other slab tears along subducting continental margins include the southern margin of Iberia and the south of Provence, leading to a faster rotation of the Corsica-Sardinia block in the late Oligocene-early Miocene.

Between 32 and 8 Ma the main driver was thus the retreat of slab pieces eastward and westward, and the related asthenospheric flow has prevented the transmission of compressional stresses across the Western Mediterranean. After 8 Ma, the resumption of N-S compression observed across the Western Mediterranean can be interpreted as the result of a recoupling of the Eurasia and Africa plate after the retreating slabs had migrated westward and eastward far enough.

As a consequence of the multiple segmentation of the two former subduction zones, several kinematic domains can be evidenced in the western Mediterranean region, which retreated in different directions with different velocities. The limits of these domains are transfer zones that form above tears in the slab. Several transfer zones are recognized, the largest one being the Catalan-Baleares-Sicily Transfer Zone. These transfer zones have different expressions, either transtensional strike-slip faults associated with syn-rift basins, crustal domes and magmatic underplating, or large-scale MCCs oriented parallel to the main shearing direction (a-type domes).

The association of a thick crust in former mountain belts and subduction-related magmatism induces a weak rheology in the overriding plate lithosphere, explaining the formation of low-angle normal faults and crustal domes, which are exhumed in back-arc basins. It probably also explains the distributed extension and the absence of simple localized strike-slip faults above slab tears, replaced by low-angle detachments and a-type domes.

Like in the eastern Mediterranean a clear link is observed between the distribution of magmatism and evolving kinematics in the back-arc region. Key-tectonic events such as the inception of back-arc extension or the formation of transfer zones, which relate at depth with slab retreat and slab tearing, are coeval with specific magmatic production like the Provençal adakites at 35–32 Ma or the migration of magmatism along the northern margin of Africa after ~20 Ma.

**Supplementary Material**

**Supplementary Material #1.** This file contains the following supplementary information: (1) Constraints used for reconstructions; (2) GPPlates rotation file references list; (3) List of features (rigid polygons) used in the reconstructions.

**Supplementary Material #2.** This file contains the GPPlates rotation file.

**Supplementary Material #3.** Figure S1: Detailed motion paths of selected points of the periphery of the Southern Tyrrenian Sea showing crossings.

The Supplementary Material is available at http://www.bsgf.fr/10.1051/bsgf/2020040/olm.

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**References**

Abbassene F, Chazot G, Bellon H, Bruguier O, Ouabadi A, Maury RC, et al. 2016. A 17 Ma onset for the post-collisional K-rich calc-alkaline magmatism in the Maghrébides: Evidence from Bougaroun (northeastern Algeria) and geodynamic implications. *Tectonophysics* 674(2016): 114–134.

Advokaat EL, van Hinsbergen DJJ, Maffione M, Langerës CG, Vissers RLM, Cherchi A, et al. 2014. Eocene rotation of Sardinia, and the paleogeography of the western Mediterranean region. *Earth Planet. Sci. Lett.* 401: 183–195. https://doi.org/10.1016/j.epsl.2014.1006.1012.

Agostini S, Doglioni C, Innocenti F, Manetti P, Tonarini S, Savaşçın MY. 2007. The transition from subduction-related to intraplate Neoene magma- tism in the Western Anatolia and Aegean area. In: Beccaluva L, Bianchini G, Wilson M, eds. *Cenozoic Volcanism in the Mediterranean Area*. Boulder: Geological Society of America, pp. 1–15. https://doi.org/10.1130/2007.2418(1101).
Alvarez W, Cocozza T, Wezel FC. 1974. Fragmentation of the Alpine orogenic belt by microplate dispersal. *Nature, News and Views* 248: 309–314.

Alvey A, Gaina C, Kusznir NJ, Torsvik TH. 2008. Integrated crustal thickness mapping and plate reconstructions for the high Arctic. *Earth and Planetary Science Letters* 274: 310–321. https://doi.org/10.1016/j.epsl.2008.1007.1036.

Argud E. 1924. La tectonique de l’Asie. In: *Proc. 13th Int. Geol. Congr.*, Brussels, pp. 171–372.

Armijo R, Meyer B, Hubert A, Barka A. 1999. Westward propagation of the north Anatolian into the northern Aegean: timing and kinematics. *Geology* 27: 267–270.

Augier R, Agard P, Jolivet L, Monié P, Robin C, Booth-Rea G. 2005a. Exhumation, doming and slab retreat in the Betic Cordillera (SE Spain): in situ 40Ar/39Ar ages and P-T-t-d paths for the Nevado-Filabride complex. *J. Metam. Geol.* 23: 357–381. https://doi.org/10.1111/j.1525-1314.2005.00581.x.

Augier R, Booth-Rea G, Agard P, Martinez-Martinez JM, Jolivet L, Azañón JM. 2005b. Exhumation constraints for the lower Nevado-Filabride Complex (Betic Cordillera, SE Spain): a Raman thermometry and Teweequ multiequilibrium thermobarometry approach. *Bull. Soc. géol Fr.* 176: 403–416. https://doi.org/10.4113/2176.2115.2403.

Augier R, Jolivet L, Robin C. 2005c. Late Orogenic doming in the eastern Betic Cordilleras: Final exhumation of the Nevado-Filabride complex and its relation to basin genesis. *Tectonics* 24: TC4003. https://doi.org/10.1029/2004TC001687.

Augier R, Robin C, Jolivet L, Booth-Rea G, Crespo-Blanc A. 2005d. Late-orogenic extension of the eastern Betics and basin genesis: the example of the Huercal-Overa basin. *Bull. Soc. Géol. France* submitted.

Augier R, Jolivet L, Do Couto D, Negro F. 2013. From ductile to brittle, late- to post-orogenic evolution of the Betic Cordillera: Structural insights from the northeastern Internal zones. *Bull soc géol France* 184: 405–425.

Avanzinelli R, Lustrino M, Mattei M, Melluso L, Conticelli S. 2009. Potassic and ultrapotassic magmatism in the circum-Tyrrhenian area: a typical anisotropy beneath SE France by SKS splitting; evidence for a Neogene asthenospheric flow induced by the Apulian slab rollback and deflected by the deep Alpine roots. *Tectonophysics* 394: 125–138.

Bach S, Cushing EM, Lemeille F, Jomard H. 2013. Updated seismotectonic zoning scheme of Metropolitan France, with reference to geologic and seismotectonic data. *Bull. Soc. géol. France* 184: 225–259.

Balgany JC, García-Dueñas V, Azañón JM, Sanchez-Gomez M. 1997. Alternating contractional and extensional events in the Alpujárride nappes of the Alboran Domain. *Tectonics* 16: 226–238.

Barchi M, Landuzzi A, Minelli M, Pialessi G. 2001. Outer Northern Apennines. In: Vai GB, Martini IP, eds. *Anatomy of an Orogen: The Apennines and Adjacent Mediterranean Basin*. London: Kluwer Publishers, pp. 215–254.

Barrier E, Vrielynck B. 2008. Paleotectonic Maps of the Middle East: Atlas of 14 Maps. Paris.

Barruol G, Granet M. 2002. A Tertiary asthenospheric flow beneath the southern French Massif Central indicated by upper mantle seismic anisotropy and related to the west Mediterranean extension. *Earth Planet. Sci. Lett.* 202: 31–47.

Barruol G, Deschamps A, Coutant O. 2004. Mapping Upper mantle anisotropy beneath SE France by SKS splitting: evidence for a Neogene asthenospheric flow induced by the Apulian slab rollback and deflected by the deep Alpine roots. *Tectonophysics* 394: 125–138.

Bayer R, Mouel JLL, Pichon XL. 1973. Magnetic anomaly pattern in the Western Mediterranean. *Earth Planet. Sci. Lett.* 19: 168–176.

Beaudoin A, Augier R, Jolivet L, Jourdon A, Raimbour H, Scaillet S, et al. 2017. Deformation behavior of continental crust during subduction and exhumation: Strain distribution over the Tenda massif (Alpine Corsica, France). *Tectonophysics* 705: 12–32. https://doi.org/10.1016/j.tecto.2017.1003.1023.

Becker TW, Facenna C. 2011. Mantle conveyor beneath the Tethyan collisional belt Earth Planet. Sci. Lett. 310: 453–461. https://doi.org/10.1016/j.epsl.2011.1008.1021.

Bellahsen N, Moutheauve F, Boutoux A, Bellanger M, Lacobme O, Jolivet L, et al. 2014. Collision kinematics in the western external Alps. *Tectonics* 33: 1055–1088. https://doi.org/10.1002/2013TC003453.

Ben Yaich A, Maaté A, Feinberg H, Magné J, Durand-Delga M. 1986. Implication of niveaux du Miocène inférieur dans les rétrochevauchements de la Dorsale calcaire rifaine (Maroc): significations à l’échelle de l’arc de Gibraltar. *C. R. Acad. Sci.* 302: 587–592.

Benouali-Mebarek N, Frizon de Lamotte D, Roca E, Bracene R, Faure JL, Sassi W, et al. 2006. Post-Cretaceous kinematics of the Atlas and Tell systems in central Algeria: Early foreland folding and subduction-related deformation. *C. R. Géoscience* 338: 115–125.

Bergerat F. 1987. Stress field in the European platform at the time of Africa-Eurasia collision. *Tectonics* 6: 99–132.

Bessière E. 2019. Evolution géodynamique des zones internes des Cordillères Bétiques (Andalousie, Espagne): apports d’une étude pluridisciplinaire du complexe Alpujárride, OSUC. Orléans: Université d’Orléans, 316 p.

Bessière E, Jolivet L, Augier R, Scaillet S, Précigout J, Azañón JM, et al. 2013. Late-orogenic extension of the eastern Betics and basin genesis: the example of the Huercal-Overa basin. *Bull. Soc. Géol. France* submitted.

Boccaletti M, Guazzzone G. 1974. Remnant arcs and marginal basins of the Alpine Corsica, France. *Bull Soc. géol France* 705: 12–32. https://doi.org/10.1016/j.tecto.2017.1003.1023.

Boccaletti M, Corti G, Martelli L. 2011. Recent and active tectonics of the external zone of the Northern Apennines (Italy). *Int J Earth Sci* 303: 394–416. https://doi.org/10.1007/s00053-010-0309-x.
Boyden JA, Müller RD, Gurnis M, Torsvik TH, Clark JA, Bosch GV, Teixell A, Jolivet M, Labaume P, Stockli D, Domènech M, Bradley KE, Vassilakis E, Hosa A, Weiss BP. 2013. Segmentation of the Palomares Fault Zone (PFZ), SE Betics, Spain. Journal of Structural Geology 26: 1615–1632. https://doi.org/10.1016/j.jsg.2004.1601.1007.

Booth-Rea G, Azañón JM, Garcia-Dueñas V, Augier R. 2005. Contrasting structural and P-T evolution of tectonic units in the southeastern Betics: Key for understanding the exhumation of the Alboran Domain HP/LT crustal rocks (western Mediterranean). Tectonics 24.

Booth-Rea G, Martinez-Martinez JM, Vidal O, Garcia-Dueñas V. 2009. Timing of Eocene Miocene thrust activity in the Western Axial Zone and Chainons Béarnais (west-central Pyrenees) revealed by multi-method thermochronology. C. R. Geoscience 348: 246–256.

Boouillon JP, Durand-Delga M, Olivier P. 1986. Betic, Rifian and Tyrrhenian arcs: distinctive features, genesis and development stage. In: Wezel FC, ed. The origin of Arcs. New York: Elsevier, pp. 281–304.

Boyden JA, Müller RD, Gurnis M, Torsvik TH, Clark JA, et al. 2011. Next-generation plate-tectonic reconstructions using GPlates. In: Keller GR, Baru C, eds. Geoinformatics: Cyberinfrastructure for the Solid Earth Sciences. Cambridge University Press, pp. 95–114.

Bozkurt E, Satr M, Bugdaycoglu C. 2011. Surprisingly young Rb/Sr ages from the Simav extensional detachment fault zone, northern Menderes Massif, Turkey. Journal of Geodynamics 52: 406–431.

Bradley KE, Vassilakis E, Hosa A, Weiss BP. 2013. Segmentation of the Hellenides recorded by Pliocene initiation of clockwise block rotation in Central Greece. Earth Planet. Sci. Lett. 362: 6–19.

Bruguier O, Bosch D, Caby R, Vitale-Brovarone A, Fernandez L, Hammar D, et al. 2017. Age of UHP metamorphism in the Western Mediterranean: Insight from rutile and minute zircon inclusions in a diamond-bearing garnet megacryst (Edough Massif, NE Algeria). Earth Planet. Sci. Lett. 474: 215–225. https://doi.org/10.1016/j.epsl.2017.1006.1043.

Brun JP, Sokoutis D. 2007.Kinematics of the Southern Rhodope Core Complex (North Greece). International Journal of Earth Science. https://doi.org/10.1007/s00531-007-0174-2.

Brunet C, Monié P, Jolivet L, Cadet JP. 2000. Migration of compression and extension in the Tyrrhenian Sea, insights from 40Ar/39Ar ages on micas along a transect from Corsica to Tuscany. Tectonophysics 321: 127–155.

Buonopent L, Bokelmann GHR, Barruol G, Morales J. 2008. Seismic anisotropy beneath southern Iberia from SKS splitting. Earth Planet. Sci. Lett. 273: 237–250. https://doi.org/10.1016/j.epsl.2008.1006.1024.

Burkhard M, Sommeragua A. 1998. Evolution of the western Swiss Molasse basin: structural relations with the Alps and the Jura belt. In: Mascle A, Puigdfebregas C, Luterbacher HP, Fernandez M, eds. Cenozoic foreland of Western Europe. Geological Society Special Publications. London: Geological Society, pp. 279–298.

Cabrer A, Roca E, Santanach P. 1988. Basin formation at the end of a strike-slip fault: the Cerdanya Basin. Journal of the Geological Society of London 145: 261–268.

Cande SC, Kent DV. 1995. Revised calibration of the geomagnetic polarity timescale for the Late Cretaceous and Cenozoic. J. Geophys. Res. 100: 6093–6095.

Canva A, Peyrefitte A, Thionin I, Couffré R, Maillard A, Jolivet L, et al. 2020. The Catalan magnetic anomaly: significance on crustal structure of the Gulf of Lion passive margin and link to the Catalan Transfer Zone. Marine and Petroleum Geology 113. https://doi.org/10.1016/j.marpetgeo.2019.104174.

Capella W, Matenco L, Dmitrieva E, Roest WMJ, Hessels S, Hsain M, et al. 2017. Thick-skinned tectonics closing the Rifian Corridor. Tectonophysics 710–711: 249–265. https://doi.org/10.1016/j.tecto.2016.1009.1028.

Capitanio FA. 2014. The dynamics of extrusion tectonics: Insights from numerical modeling. Tectonics 33: 2361–2381. https://doi.org/10.1002/2014TC003688.

Carey SW. 1958. A tectonic approach to continental drift. In: Carey SW, ed. Continental Drift: A Symposium. Hobart: Geology Department, University of Tasmania, pp. 177–355.

Caricchi C, Cifelli F, Sagnotti L, Sani F, Speranza F, Mattei M. 2014. Paleomagnetic evidence for a post-Eocene 90° CCW rotation of internal Apennine units: a linkage with Corsica-Sardinia rotation? Tectonics 33: 374–392.

Carminati E, Wörtel MJR, Meijer PT, Sabadini R. 2001. High pressure-low temperature metamorphism and polyphase Alpine deformation at Sant’ Andrea di Cotone (Eastern Corsica, France). Tectonophysics 321: 127–155.

Casas Sainz AM, Facenna C. 2001. Tertiary compression deformation of the Iberian plate. Terra Nova 13: 281–288.

Casula G, Cherchi A, Montadert L, Murr M, Sarria E. 2001. The Cenozoic graben system of Sardinia (Italy): geodynamic evolution from new seismic and field data. Marine and Petroleum Geology 18, 863–888.

Cavazzza W, DeCelis PG, Fellin MG, Paganelli L. 2007. The Miocene Saint-Florent Basin in northern Corsica: stratigraphy, sedimentology, and tectonic implications. Basin Research. https://doi.org/10.1111/j.1365-2117.2007.00334.x.
Chevrot S, Sylvander M, Diaz J, Martin R, Mouthereau F, Manatschal Chalouan A, Michard A, El Kadiri K, Negro F, Soto JI, Chalouan A, Galindo-Zaldivar J, Akili M, Marin C, Chabli A, Ruano Cirrincione R, Fazio E, Fiannacca P, Ortolano G, Pezzino A, Punturo Cohen CR. 1980. Plate tectonic model for the Oligoco-Miocene evolution of the Western Mediterranean and North Africa. London, pp. 37–59. Geological Society Special Publications.

Collettini C, Holdsworth RE. 2004. Fault zone weakening and character of slip along low-angle normal faults: insights from the Zuccale fault, Elba, Italy. J. Geol. Soc. London 161: 1039–1051.

Coltice N, Husson L, Faccenna C, Arnould M. 2019. What drives tectonic plate dynamics? Sciences Advances 5: eaax4295.

Comas MC, Garcia-Duenas V, Jurado MJ. 1992. Neogene tectonic evolution of the Alboran Sea from MCS data. Geo. Mar. Lett. 12: 157–164.

Comas MC, Platt JP, Soto JI, Watts AB. 1999. The origin and tectonic history of the Alboran basin: insights from Leg 161 results. In: Zahn R, Comas MC, Klaus A, eds. Proc. ODP Sci. Results. TX: (Ocean Drilling Program), College Station, pp. 555–582.

Corno FH, Burlet D. 1992. Stress field determination in France by hydraulic test in boreholes. J. Geophys. Res. 97: 11829–11849.

Coulon C, Megartsi M, Maury RC, Bellon H, Louni-Hacini A, Cotten E, Hercil G, et al. 2005. Post-collisional transition from calc-alkaline to alkaline volcanism during the Neogene in Oranie (Algeria): magmatic expression of a slab breakoff. Lithos 62: 87–110.

Crespo-Blanc A. 1995. Inversion pattern of extensional fault systems: a case study of the Miocene rifting of the Alboran basement (North of Sierra Nevada, Betic Chain). J. Struct. Geol. 17: 1559–1569.

Crespo-Blanc A, Frizon de Lamotte D. 2006. Structural evolution of the external zones derived from the flysch trough and the south Iberian and Maghrebien paleomargins around the Gibraltar arc: a comparative study. Bull. soc. geol. France 177: 267–282.

Crespo-Blanc A, Orozco M, Garcia-Duenas V. 1994. Extension versus compression during the Miocene tectonic evolution of the Betic chain. Late folding of normal fault system. Tectonics 13: 78–88.

Crespo-Blanc A, Comas M, Balanyà JC. 2016. Clues for a Tortonian reconstruction of the Gibraltar Arc: Structural pattern, deformation diachronism and block rotations. Tectonophysics 683: 308–324. https://doi.org/10.1016/j.tecto.2016.1005.1045.

d’Acremont E, Lafosse M, Rabaste A, Teuquey G, Do Couto D, Ercilla G, et al. 2020. Polyphase tectonic evolution of fore-arc basin related to STEP fault as revealed by seismic reflection data from the Alboran Sea (W-Mediterranean). Tectonics. https://doi.org/10.1029/2019TC005885.

Daniel JM, Jolivet L. 1995. Detachment faults and pluton emplacement, Elba Island (Tyrrenhian Sea). Bull. Soc. géol. France 166: 341–354.

Daniel JM, Jolivet L, Goffè P, Poinssot C. 1996. Crustal-scale strain partitioning: footwall deformation below the Alpine Corsica Oligo-Miocene detachment. J. Struct. Geol. 18: 41–59.

Dannowski A, Kopp H, Grevesemeyer I, Lange D, Bialas J, Thowart M, Bialas J, et al. 2020. Seismic evidence for failed rifting in the Ligurian basin related to STEP fault as revealed by seismic reprocessing. Geol. Soc. Special Publications. London, pp. 37–63.

Dannowski A, Kopp H, Grevesemeyer I, Lange D, Bialas J, Thowart M, Bialas J, et al. 2020. Seismic evidence for failed rifting in the Ligurian basin related to STEP fault as revealed by seismic reprocessing. Geol. Soc. Special Publications. London, pp. 37–63.

Dannowski A, Kopp H, Grevesemeyer I, Lange D, Bialas J, Thowart M, Bialas J, et al. 2020. Seismic evidence for failed rifting in the Ligurian basin related to STEP fault as revealed by seismic reprocessing. Geol. Soc. Special Publications. London, pp. 37–63.

Dannowski A, Kopp H, Grevesemeyer I, Lange D, Bialas J, Thowart M, Bialas J, et al. 2020. Seismic evidence for failed rifting in the Ligurian basin related to STEP fault as revealed by seismic reprocessing. Geol. Soc. Special Publications. London, pp. 37–63.

Dannowski A, Kopp H, Grevesemeyer I, Lange D, Bialas J, Thowart M, Bialas J, et al. 2020. Seismic evidence for failed rifting in the Ligurian basin related to STEP fault as revealed by seismic reprocessing. Geol. Soc. Special Publications. London, pp. 37–63.

Dannowski A, Kopp H, Grevesemeyer I, Lange D, Bialas J, Thowart M, Bialas J, et al. 2020. Seismic evidence for failed rifting in the Ligurian basin related to STEP fault as revealed by seismic reprocessing. Geol. Soc. Special Publications. London, pp. 37–63.

Dannowski A, Kopp H, Grevesemeyer I, Lange D, Bialas J, Thowart M, Bialas J, et al. 2020. Seismic evidence for failed rifting in the Ligurian basin related to STEP fault as revealed by seismic reprocessing. Geol. Soc. Special Publications. London, pp. 37–63.

Dannowski A, Kopp H, Grevesemeyer I, Lange D, Bialas J, Thowart M, Bialas J, et al. 2020. Seismic evidence for failed rifting in the Ligurian basin related to STEP fault as revealed by seismic reprocessing. Geol. Soc. Special Publications. London, pp. 37–63.
2003 Mw-6.8 Boumerdes earthquake. *EOS Trans. AGU* 84: S42E–S42F.

Dewey JF, Helman ML, Torco E, Hutton DHW, Knott SD. 1989. Kinematics of the Western Mediterranean. In: Coward MP, Dietrich D, Park RG, eds. *Alpine Tectonics*, pp. 265–283.

Dézes P, Schmid SM, Ziegler PA. 2004. Evolution of the European Cenozoic Rift System: interaction of the Alpine and Pyrenean orogens with their foreland lithosphere. *Tectonophysics* 389: 1–33.

Di Staso A, Perrone V, Perrotta S, Zaghoul MN, Durand-Delga M. 2010. Stratigraphy, age and petrography of the Beni Issef successions (External Rif, Morocco): Insights for the evolution of the Maghrebian Chain. *C. R. Geoscience* 342: 718–746.

Diaz J, Gallart J, Moraí A, Silveira G, Pedreira D, Pulgar JA, et al. 2015. From the Bay of Biscay to the High Atlas: Completing the anisotropic characterization of the upper mantle beneath the westernmost Mediterranean region. *Tectonophysics* 663: 192–202.

Díeck Y, Bentran S, Albaret E, Brassac C, Moretti A, et al. 2019. Mapping the crustal structure beneath the eastern Pyrenees. *Tectonophysics* 744: 296–309. https://doi.org/10.1016/j.tecto.2018.1007.1011.

Dielforder A, Frasca G, Brune S, Ford M. 2019. Formation of the Iberian-European Convergent Plate Boundary Fault and Its Effect on Intraplate Deformation in Central Europe. *Geochem. Geophy. Geosyst.* https://doi.org/10.1029/2018GC007840.

Dilek Y, Altunkaynak S. 2009. Geochemical and temporal evolution of Cenozoic magmatism in western Turkey: mantle response to collision, slab break-off, and lithospheric tearing in an orogenic belt. In: van Hinsbergen DJJ, Edwards DJJ, Govers R, eds. *Collision and Collapse at the Africa–Arabia–Eurasia Subduction Zone*. London: The Geological Society, pp. 213–233.

Do Couto D, Giumiaux C, Augier R, Lebret N, Folcher N, Jouannic G, et al. 2014. Tectonic inversion of an asymmetric graben: Insights from a combined field and gravity survey in the Sorbas basin. *Tectonics* 33. https://doi.org/10.1002/2013TC003458.

Do Couto D, Gorini C, Jolivet L, Lebret N, Augier R, Giumiaux C, et al. 2016. Tectonic and stratigraphic evolution of the Western Algerian Basin in the last 25 Myrs. *Tectonophysics*. https://doi.org/10.1016/j.tecto.2016.1003.1020.

Doglioni C, Busatta C, Bolis G, Marianini L, Zanella M. 1996. Structural evolution of the eastern Balkans (Bulgaria). *Marine and Petroleum Geology* 13: 225–251.

Doglioni C, Gueguen E, Sábat F, Fernandez M. 1997. The Western Mediterranean extensional basins and the Alpine orogen. *Terra Nova* 9: 109–112.

Driussi O, Briaia A, Maillard A. 2015. Evidence for transform motion along the South Balearic margin and Implications for the kinematics of opening of the Algerian basin. *Bull. Soc. géol. France* 186: 353–370.

Duchêne S, Blichert-Toft J, Luais B, Petrov V, Zaghoul MN, Durand-Delga M. 1997. The Lu-Hf dating of garnets and the ages of the Alpine Tectonics. *Contrib. Mineral. Petrol.* 156: 577–593.

Duggen S, Hoernle KA, Hauff F, Clügel A, Bouabdellah M, Thirlwall MF. 2009. Flow of Canary mantle plume material through a subcontinental lithospheric corridor beneath Africa to the Mediterranean. *Geology* 37: 283–286. https://doi.org/10.1130/G25426A.25421.

El Kadri K, Hília R, Sanz de Galdeano C, Lopez-Garrido AC, Chalouan A, Serrano F, et al. 2006. Regional correlations across the Intermedes-Externides front (northwestern Rif Belt, Morocco) during the Late Cretaceous-Early Burdigalian times: palaeogeo-graphical and palaeotectonic implications. In: Moratti G, Chalouan A, eds. *Tectonics of the Western Mediterranean and North Africa*, Special Publications. London: Geological Society, pp. 193–215.

Elsasser WM. 1968. The mechanics of continental drift. *Proceedings of the American Philosophical Society* 112: 344–353.

Espurt N, Hippolyte JC, Saillard M, Belhier O. 2012. Geometry and kinematic evolution of a long-living foreland structure inferred from field data and cross section balancing, the Sainte-Victoire System, Provence, France. *Tectonics* 31: TC4021. https://doi.org/10.1029/2011TC002988.

Esteban JJ, Sanchez-Rodriguez L, Seward D, Cuevas J, Tubia JM. 2004. The late thermal history of the Ronda area, southern Spain. *Tectonophysics* 389: 81–92. https://doi.org/10.1016/j.tecto.2004.1007.1050.

Esteban JJ, Cuevas J, Tubia JM, Sergeev S, Larionov A. 2011. A revised Aquitanian age for the emplacement of the Ronda peridotites (Betic Cordilleras, southern Spain). *Geol Mag* 148: 183–187.

Esteban JJ, Tubia JM, Cuevas J, Seward D, Larionov A, Sergeev S, et al. 2013. Insights into extensional events in the Betic Cordilleras, southern Spain: New fission-track and U-Pb SHRIMP analyses. *Tectonophysics* 603: 179–188. https://doi.org/10.1016/j.tecto.2013.1005.1027.

Estrada F, Galindo-Zaldívar J, Vázquez JT, Ercilla G, D’Acremont E, Alonso B, et al. 2017. Tectonic indentation in the central Algerian Sea (westernmost Mediterranean). *Terra Nova* 30: 24–33. https://doi.org/10.1111/ter.12304.

Etheve N, Mohn G, Martos R, Roca E, Blanpied C. 2016. Extensional vs contractional Cenozoic deformation in Ibiza (Balearic Promontory, Spain): Integration in the Western Mediterranean back-arc setting. *Tectonophysics* 682: 35–55. https://doi.org/10.1016/j.tecto.2016.1005.1037.

Etheve N, Mohn G, Frizon de Lamotte D, Roca E, Tugend J, Gómez-Romeu J. 2018. Extreme Mesozoic crustal thinning in the eastern Iberia margin: The example of the Columbrets Basin (Valencia Trough). *Tectonics* 37. https://doi.org/10.1002/2017TC004613.

Faccenna C, Becker TW. 2010. Shaping mobile belts by small-scale convection. *Nature* 465: 602–605. https://doi.org/10.1038/nature09064.

Faccenna C, Becker TW, Lucente FP, Jolivet L, Rossetti F. 2001a. History of subduction and back-arc extension in the Central Mediterranean. *Geophys. J. Int.* 145: 809–820.

Faccenna C, Fucinelli F, Giardini D, Lucente P. 2001b. Episodic back-arc extension during restricted mantle convection in the Central Mediterranean. *Earth Planet. Sci. Lett.* 187: 105–116.

Faccenna C, Jolivet L, Piromallo C, Morelli A. 2003. Subduction and the depth of convection in the Mediterranean mantle. *J. Geophys. Res.* 108: 2099. https://doi.org/10.1029/2001JB001690.

Faccenna C, Piromallo C, Crespo-Blanc A, Jolivet L, Rossetti F. 2004. Lateral slab deformation and the origin of the Western
Faccenna C, Civetta L, D’Antonio M, Fucinelli F, Margheriti L, Piromallo C. 2005. Constraints on mantle circulation around the deforming Calabrian slab. Geophys Res. Lett. 32: L06311. https://doi.org/10.1029/2002TC001488.

Faccenna C, Civetta L, D’Antonio M, Fucinelli F, Margheriti L, Piromallo C. 2007. Slab disruption, mantle circulation, and the opening of the Tyrrhenian basins. In: Beccaluva L, Bianchini G, Wilson M, eds. Cenozoic Volcanism in the Mediterranean Area, pp. 153–169. https://doi.org/10.1130/2010.2188(1108).

Faccenna C, Becker TW, Conrad CP, Husson L. 2013a. Mountain building and mantle dynamics. Tectonics 32: 80–93. https://doi.org/10.1029/2012TC003176.

Faccenna C, Becker TW, Julivet L, Keskin M. 2013b. Mantle convection in the Middle East: Reconciling Afar upwelling, Arabia indentation and Aegean trench rollback. Earth Planet. Sci. Lett. 375: 254–269. https://doi.org/10.1016/j.epsl.2013.1005.1043.

Faccenna C, Becker TW, Auer L, Billi A, Boschi L, Brun JP, et al. 2014. Mantle dynamics in the Mediterranean. Reviews of Geophysics 52: 283–332. https://doi.org/10.1002/2013RG000444.

Farina F, Dini A, Innocenti F, Rocchi S, Westerman DS. 2010. Rapid incremental assembly of the Monte Capanne pluton (Elba Island, Tuscany) by downward stacking of magma sheets. GSA Bulletin 122: 1463–1479. https://doi.org/10.1130/B30112.30111.

Fauré M, Malavieille J. 1981. Étude structurale d’un cisaillement ductile: le charriage ophiolitique Corse dans la région de Bastia. Bull. Soc. géol. France 23: 335–343.

Fernández M, Torne M, Vergès J, Casiello E, Macchiaveli C. 2019. Evidence of Segmentation in the Iberia–Africa Plate Boundary: A Jurassic Heritage? Geosciences 9: 343. https://doi.org/10.3390/geosciences9080343.

Ferrandini M, Ferrandini J, Löye-Pilot M-D, Butterlin J, Cravatte J, Janin MC. 1996. Le Miocène du bassin de Saint Florent (Corse): modalités de la transgression du Burdigalien supérieur et mise en évidence du Serravallien. Geobios 31: 125–137.

Fichtner A, Villasenór A. 2015. Crust and upper mantle of the western Mediterranean – Constraints from full-waveform inversion. Earth Planet. Sci. Lett. 428: 52–62. https://doi.org/10.1016/j.epsl.2015.1007.1038.

Fitzgerald PG, Muniòz JA, Coney PJ, Baldwin SL. 1999. Asymmetric exhumation across the Pyrenean orogen: Implications for the tectonic evolution of a collisional orogen. Earth Planet. Sci. Lett. 173: 157–170.

Ford M, Dhuime S, Gasquet D, Vanderhaeghe O. 2006. Two-phase orogenic convergence in the external and internal SW Alps. J. Geol. Soc London 163: 815–826.

Fournier M, Julivet L, Goffé B, Dubois R. 1991. The Alpine Corsica metamorphic core complex. Tectonics 10: 1173–1186.

Fournier F, Tassy A, Thinion I, Münch P, Cornée JJ, Borghomano J, et al. 2016. Pre-Pliocene tectonostratigraphic framework of the Provence continental shelf (eastern Gulf of Lion, SE France). Bull. Soc. géol. France 187: 187–216.

Frascas G, Gueydan F, Brun JP. 2015. Structural record of lower miocene westward Alboran domain motion in the western Betics (southern Spain). Tectonophysics 657: 1–20.

Frascas G, Gueydan F, Brun JP, Monie P. 2016. Deformation mechanisms in a continental rift up to mantle exhumation. Field evidence from the western Betics, Spain. Marine and Petroleum Geology 76: 310–328. https://doi.org/10.1016/j.marpetgeo.2016.1004.1020.

Frasca G, Gueydan F, Poujol M, Brun JP, Patat F, Monié P, et al. 2017. Fast switch from extensional exhumation to thrusting of the Ronda Peridotites (South Spain). Terra Nova 29: 117–126.

Frizon de Lamotte D, Saint Bezaz B, Bracène R, Mercier E. 2000. The two main steps of the Atlas building and geodynamics of the West Mediterranean. Tectonics 19: 740–761.

Frizon de Lamotte D, Crespo-Blanc A, Saint-Bézar B, Comas M, Fernández M, Zeyen H, et al. 2004. Transect I: Iberia-Meseta – Guadalquivir Basin – Betic Cordillera – Alboran Sea; Rift – Moorcan Meseta – High Atlas – Sahara Domain. In: Cavazza W, Roure FM, Spakman W, StampflI GM, eds. The TRANSMED Atlas – The Mediterranean region from crust to mantle. Berlin, Heidelberg: Springer.

Frizon de Lamotte D, Zizi M, Missenard Y, Hafid M, El Azouzzi M, Charriere A, et al. 2008. The Atlas system. In: Michard A, Sadadi O, Chalouan A, Frizon de Lamotte D. eds. Continental Evolution: The Geology of Morocco. Heidelberg: Springer-Verlag, pp. 133–202.

Frizon de Lamotte D, Raulin C, Mouchot N, Wrobel-Daveau JC, Blanpied C, Ringenbach JC. 2011. The southernmost margin of the Tethys realm during the Mesozoic and Cenozoic: Initial geometry and timing of the inversion processes. Tectonics 30: TC3002. https://doi.org/10.1029/2010TC002691.

Gabas A, Macau A, Benjumea B, Queralt P, Ledo J, Figueras S, et al. 2016. Joint Audio-Magnetotelluric and Passive Seismic Imaging of the Cerdanya Basin. Surv Geophys 37: 897–921. https://doi.org/10.1007/s10712-016-1937-2-10714.

Gaetani M, Dercourt J, Vrielinck B. 2003. The Peri-Tethys Programme: achievements and results. Episodes 26: 79–93.

Gaima C, Gernigon L, Ball P. 2009. Palaeocean–Recent plate boundaries in the NE Atlantic and the formation of the Jan Mayen microcontinent. Journal of the Geological Society, London 166: 601–616. https://doi.org/10.1144/0161-76492208-76492112.

Galindo-Zaldívar J, González-Lodeiro F, Jabaloy A. 1989. Progressive extensional shear structures in a detachment contact in the Western Sierra Nevada (Betic Cordilleras, Spain). Geodinamica Acta 3: 73–85.

Galindo-Zaldívar J, Jabaloy A, Serrano I, Morales J, Gonzale- Lodeiro F, Torcal F. 1999. Recent and present-day stresses in the Granada Basin (Betic Cordilleras): Example of a late Miocene-present-day extensional basin in a convergent plate boundary. Tectonics 18: 686–702.

García-Castellanos D, Villaseñor A. 2011. Messinian salinity crisis regulated by competing tectonics and erosion at the Gibraltar arc. Nature 480: 359–365. https://doi.org/10.1038/nature10651.

Gattacceca J. 2000. Cinématique du bassin liguro-provençal entre 30 et 12 Ma. Implications géodynamiques. École des Mines de Paris, École Nationale Supérieure des Mines de Paris, 293 p.

Gattacceca J, Deino A, Rizzo R, Jones DS, Henry B, Beaudoin B, et al. 2007. Miocene rotation of Sardinia: New paleomagnetic and geochronological constraints and geodynamic implications. Earth Planet. Sci. Lett. 258: 359–377. https://doi.org/10.1016/j.epsl.2007.1002.1003.

Gernigon L, Olesen E, Ebbing J, Wienceck S, Gaima C, Mogard JO, et al. 2012. Geophysical insights and early spreading history in the vicinity of the Jan Mayen Fracture Zone, Norwegian–Greenland Sea. Tectonophysics 468: 185–205. https://doi.org/10.1016/j.tecto.2008.1004.1025.

Giannineri G. 1980–1981. Analyse structurale de la bordure méridionale de l’Arc de Castellane entre Mons et Bargème (Var): relations entre les déformations tectoniques et la sédimentation au cours du Tertiaire. Bull BRGM Fr. 2: 43–67.
Gibbons CW, Warburton J. 1986. The blueschist facies schistose lustrés of Alpine Corsica: a review. *Geol. Soc. Am. memoir* 164: 301–311.

Gimeno-Vives O, Mohn G, Bosse V, Haissen F, Zagalhou MN, Atouabat A, et al. 2019. The Mesozoic margin of the Maghrebian Tethys in the Rif belt (Morocco): Evidence for polyphase rifting and related magmatic activity. *Tectonics* 38: 2894–2918. doi.org/10.1002/2019TC005508.

Gomez F, Almendinger R, Baranangi M, Er-Raji A, Dahmani M. 1998. Crustal shortening and vertical strain partitioning in the Middle Atlas Mountains of Morocco. *Tectonics* 14: 520–533.

Gömze-Pugnaire MT, Nietzsche F, Abad I, Veilina N, Garrido CJ, Acosta-Vigil A, et al. 2019. Alpine Metamorphism in the Bettic Internal Zones. In: Quesada C, Oliveira JT, eds. *The Geology of Iberia: A Geodynamic Approach*. Springer Nature Switzerland AG. https://doi.org/10.1007/978-1003-1030-11295-11290_11123.

Gorini C, Le Marrec A, Mauffret A. 1993. Contribution to the structural and sedimentary history of the Gulf of Lions (western Mediterranean), from the ECORS profiles, industrial seismic profiles and well data. *Bull. geol. Soc. France* 164: 353–363.

Gorini C, Mauffret A, Guennoc P, Le Marrec A. 1994. Structure of the Gulf of Lions (Northwestern Mediterranean Sea): a review. In: Mascele A, ed. *Hydrocarbon and Petroleum Geology of France*. Springer-Verlag, pp. 223–243.

Govers R, Wortel MJR. 2005. Lithosphere tearing at STEP faults: Implication for the geodynamic evolution of the Alboran domain. *Tectonophysics* 722: 507–533. doi.org/10.1016/j.tecto.2017.1011.1028.

Hsu KJ, Ryan WBF, Cita MB. 1973. Late Miocene desiccation of the Mediterranean. *Nature* 242: 240–244.

Hsu KJ, Montardet L, Bernoulli D, Cita MB, Erickson A, Garrison RE, et al. 1978. History of the Messinian salinity crisis. In: Hsu KJ, Montardet L, et al., eds. *Initial Reports of the Deep Sea Drilling Project*. Washington: U.S. Government Printing Office, pp. 1053–1078.

Iribarren L, Vergés J, Camurri F, Fullea J, Fernández M. 2007. The structure of the Atlantic–Mediterranean transition zone from the Alboran Sea to the Horseshoe Abyssal Plain (Iberia–Africa plate boundary). *Marine Geology* 243: 97–119. doi.org/10.11011/j.margeo.2007.1005.1011.

Iribarren L, Vergés J, Fernández M. 2009. Sediment supply from the Betics–Rif orogen to basins through Neogene. *Tectonophysics* 475: 68–84. doi.org/10.1016/j.tecto.2008.1011.1029.

Jabaloy A, Galindo-Saldivar J, Gonzales-Lodeiro F. 1993. The Alpujarride-Nevado-Filábrides extensional shear zone, Betic Cordillera, SE Spain. *J. Struct. Geol.* 15: 555–569.

Jaffey N, Robertson AHF. 2001. New sedimentological and structural data from the Eccemis Fault Zone, southern Turkey: implications for its timing and offset and the Cenozoic tectonic escape of Anatolia. *J Geol Soc Lond.* 158: 367–378.

Janowski M, Loget N, Gautheron C, Barbarand J, Bellahsen N, Van Den Driesche J, et al. 2017. Neogene exhumation and relief evolution in the eastern Betics (SE Spain): Insights from the Sierra de Gador. *Terra Nova*, 1–7. doi.org/10.1111/ter.12252.

Johnson C, Harbury N, Hurford AJ. 1997. The role of extension in the Miocene denudation of the Nevado-Filábrides Complex, Betic Cordillera (SE Spain). *Tectonics* 16: 189–204.

Jolivet L, Brune JP. 2010. Cenozoic geodynamic evolution of the Aegean region. *Int. J. Earth Science* 99: 109–138. doi.org/10.11007/s00531-0008-0036-600353.

Jolivet, L., Faccenna, C. 2000. Mediterranean extension and the Africa-Eurasia collision. *Tectonics* 19: 1095–1106. doi.org/10.1029/2000TC900018.

Jolivet L, Dubois R, Fournier M, Goffé B, Michaud A, Jourdan C. 1997. The Mesozoic margin of the Maghrebian Africa plate boundary. *Lithos* 38: 250–269.

Kuehler A, Bouillin JP, Compagnoni R. 2019. Alpine Corsica: a review. *Bull. Soc. geol. France* 8: 257–267.

Heymes T, Monié P, Arnaud N, Pêcher A, Bouillou JP, Compagnoni R. 2010. Alpine tectonics in the Calabrian–Peloritan belt (southern Italy): New 40Ar/39Ar data in the Aspromonte Massif area. *Lithos* 114: 451–472. doi.org/10.1016/j.lithos.2009.1010.1011.

Honnemay E, Corsini M, Lardeaux JM, Romagny A, Münch P, Bosch D, et al. 2018. Miocene crustal extension following thrust tectonics in the Lower Sebtides units (internal Rif, Ceuta Peninsula, Spain). *Tectonophysics* 535. https://doi.org/10.1016/j.tecto.2017.1011.1028.

Hsu KJ, Ryan WBF, Cita MB. 1973. Late Miocene desiccation of the Mediterranean. *Nature* 242: 240–244.

Jolivet L, Daniel JM, Fournier M. 1991. Geometry and kinematics of ductile extension in alpine Corsica. *Earth and Planetary Science Letters* 104: 278–291.

Jolivet L, Daniel JM, Truffert C, Goffé B. 1994. Exhumation of deep crustal metamorphic rocks and crustal extension in back-arc regions. *Lithos* 33: 3–30. doi.org/10.1016/0024-4937(94)90051-90055.

Jolivet L, Goffé B, Monié P, Truffert-Luxey C, Patriat M, Bouneau M. 1996. Miocene detachment in Crete and exhumation P-T-t paths of high pressure metamorphic rocks. *Tectonics* 15: 1129–1133.

Jolivet L, Faccenna C, Goffé B, Mattei M, Rossetti F, Brunet C, et al. 1998. Mid-crustal shear zones in post-orogenic extension: the northern Tyrrhenian Sea case. *J. Geophys. Res. 103*: 12123–12160. doi.org/12110.11029/12197JB03616.
Jolivet L, Faccenna C, Goffé B, Burov E, Agard P. 2003. Subduction tectonics and exhumation of high-pressure metamorphic rocks in the Mediterranean orogens. Am. J. Science 303: 353–409. https://doi.org/10.1190/1.1564271.

Jolivet L, Famin V, Mehl C, Parra T, Aubourg C, Hébert R, et al. 2004. Strain localization during crustal-scale boudinage to form extensional metamorphic domes in the Aegean Sea. In: Whitney DL, Teyssier C, Siddoway CS, eds. Neuss domes in orogeny. Boulder, Colorado: Geological Society of America, pp. 185–210.

Jolivet L, Augier R, Robin C, Suc JP, Rouchy JM. 2006. The dynamics of rifting in back-arc basins: The Gulf of Lion margin. Tectonophysics 426: 165–185.

Kastens KA, Mascle J. 1990. The geological evolution of the Tyrrhenian Sea: an introduction to the scientific results of ODP Leg 107. In: Kastens KA, Mascle JC, et al., eds. Proc. ODP. Scientific Results, pp. 3–26.

Kastens K, Mascle J, Auroux C, Bonatti E, Broglio C, Channell J, et al. 1988. ODP Leg 107 in the Tyrrhenian Sea: insight into passive margin and back-arc basin evolution. Geological Society of America Bulletin 100: 1140–1156.

Keller JV, Piali G. 1990. Tectonics of the island of Elba: a reappraisal. Bull. Soc. Geol. It. 109: 413–425.

Kissel C, Laj C. 1988. The Tertiary geodynamic evolution of the Aegean arc: a paleomagnetic reconstruction. Tectonophysics 146: 183–201.

Kissel C, Averbuch O, Frizon de Lamotte D, Monod O, Allerton S. 1993. First paleomagnetic evidence for a post-Eocene clockwise rotation of the Western Taourides thrust belt east of the Isparta reentrant (Southwestern Turkey). Earth Planet Sci Lett 117: 1–14.

Kissel C, Laj C, Poisson A, Görür N. 2002. Paleomagnetic reconstruction of the cenozoic evolution of the eastern Mediterranean. Tectonophysics 362: 199–217.

Kounov A, Seward D, Burg JP, Stockli D, Wüthrich E. 2012. Cenozoic thermal evolution of the Central Rhodope Metamorphic Complex (Southern Bulgaria). International Journal of Earth Sciences. https://doi.org/10.1007/s00531-00020-01862-00534.

Krijgsman W, Hilgen FJ, Raffi I, Sierra FJ, Wilson DS. 1999. Chronology, causes and progression of the Messinian salinity crisis. Nature 400: 652–655.

Labails C, Olivet JL, Aslanian D, Roest WR. 2010. An alternative early opening scenario for the Central Atlantic Ocean. Earth Planet. Sci. Lett. 297: 355–368. https://doi.org/10.1016/j.epsl.2010.10.024.

Labarue M, Peresse F, Jolivet M, Teixell A, Lahfid A. 2016. Tectonothermal history of an exhumed thrust-sheet-top basin: An example from the south Pyrenean thrust belt. Tectonics 35: 1280–1313. https://doi.org/10.1002/2016TC004192.

Lacombe O, Jolivet L. 2005. Structural and kinematic relationships between Corsica and the Pyrenees-Provence domain at the time of the Pyrenean orogeny. Tectonics 24: TC1003. https://doi.org/10.1029/2004TC001673.

Lafosse M, Gorinia C, Le Roy P, Alsono B, d’Acremont E, Ercilla G, et al. 2018. Late Pleistocene-Holocene history of a tectonically active segment of the western continental margin (Nekor basin, Western Mediterranean, Morocco). Marine and Petroleum Geology 97: 370–389. https://doi.org/10.1016/j.marpetgeo.2018.10.022.

Lafosse M, d’Acremont E, Rabate A, Estrada F, Jolivet-Castelot M, Vazquez JT, et al. 2020. Plio-Quaternary tectonic evolution of the southern margin of the Alboran Basin (Western Mediterranean). Solid Earth 11: 741–765. https://doi.org/10.5194/se-11-741-2020.

Lawer LA, Müller RD, Srivastava SP, Roest W. 1990. The opening of the Arctic Ocean. In: Blei U, Thiede J, eds. Geological history of...
Martinez-Martinez JM, Azañon JM. 1997. Mode of extensional tectonics in the southeastern Betics (SE Spain): implications for the tectonic evolution of the peri-Alboran orogenic system. Tectonics 16: 205–225.

Martinez-Martinez JM, Booth-Rea G, Azañon JM, Torcal F. 2006. Active transfer fault zone linking a segmented extensional system (Betics, southern Spain): Insight into heterogeneous extension driven by edge delamination. Tectonophysics 422: 159–173. https://doi.org/10.1016/j.tecto.2006.1006.1001.

Mattauer M, Faure M, Malavieille J. 1981. Transverse lineation and large scale structures related to Alpine obduction in Corsica. J. struct. Geol. 3: 401–409.

Mattei M, Cifelli F, Rojas M, Crespo-Blanc A, Comas M, Faccenna C, et al. 2006. Neogene tectonic evolution of the Gibraltar Arc: New paleomagnetic constrains from the Betic chain. Earth and Planetary Science Letters 250: 522–540. https://doi.org/10.1016/j.epsl.2006.1008.1012.

Mauffret A, Pascal G, Maillard A, Gorini C. 1995. Tectonics and deep structure of the north-western Mediterranean basin. Marine and Petroleum Geology 12: 645–666.

Mauffret A, Frizon de Lamotte D, Lallemant S, Gorini C, Maillard A. 2004. E-W opening of the Algerian basin (Western Mediterranean). Terra Nova 16: 257–264.

Mauffret A, Ammar A, Gorini C, Jabour H. 2007. The Alboran Sea (Western Mediterranean) revisited with a view from the Moroccan Margin. Terra Nova 19: 195–203.

Maury RC, Fourcade S, Coulenc E, El Azzouzia M, Bellona H, Coutelle A, et al. 2000. Post-collisional Neogene magmatism of the Mediterranean Maghreb margin: a consequence of slab breakoff. C. R. Acad. Sci. Paris, Sciences de la Terre et des planètes / Earth and Planetary Sciences 331: 159–173.

Mazzoli S, Martin-Algarra A. 2011. Deformation partitioning through transpressional emplacement of a “mantle extrusion wedge”: the Ronda peridotites, western Betic Cordillera, Spain. Journal of the Geological Society, London 168: 373–382. https://doi.org/10.1144/1080-6343-20050904.

Mazzoli S, Martin-Algarra A, Reddy SM, Lopez Sanchez-Vizcaíno V, Fedele L, Noviello A. 2013. The evolution of the footwall to the Ronda subcontinental mantle peridotites: insights from the Nieves Unit (western Betic Cordillera). Journal of the Geological Society, London 170: 385–402. https://doi.org/10.1144/jgs2012-1105.

McKenzie DP. 1969. Speculations on the consequences and causes of the Alpine orogenic system. Tectonics 16: 205–225.

Melchorre M, Vergés J, Fernández M, Coltorti M, Torne M, Casciello E. 2017. Evidence for mantle heterogeneities in the westernmost Mediterranean from a statistical approach to volcanic petrology. Lithos 276: 62–74. https://doi.org/10.1016/j.lithos.2016.1011.1018.

Menant A, Jolivet L, Vrietynck B. 2016a. Kinematic reconstructions and magmatic evolution illuminating crustal and mantle dynamics of the eastern Mediterranean region since the late Cretaceous. Tectonophysics 675: 103–140. https://doi.org/10.1016/j.tecto.2016.1003.1007.

Menant A, Sternai P, Jolivet L, Guillou-Frottier L, Gerya T. 2016b. 3D numerical modeling of mantle flow, crustal dynamics and magma genesis associated with slab rollback and tearing: The eastern Mediterranean case. Earth Planet. Sci. Lett. 442: 93–107. https://doi.org/10.1016/j.epsl.2016.1003.1002.

Michard A, Chalouan A, Feinberg H, Goffé B, Montigny R. 2002. How does the Alpine belt end between Spain and Morocco? Bull. geol. soc. France 173: 3–15.

Michard A, Negro F, Saddiqi O, Bouyaouene ML, Chalouan A, Montigny R, et al. 2006. Pressure-temperature-time constraints on the Maghrebide mountain building: evidence from the Rif-Betic transect (Morocco, Spain), Algerian correlations, and geodynamic implications. C. R. Geoscience 338: 92–114.

Molli G, Malavieille J. 2010. Orogenic processes and the Corsica/ Apenines geodynamic evolution: insights from Taiwan. Int J Earth Sci (Geol Rundsch). https://doi.org/10.1007/s00531-009-00598-x.

Molli G, Tribuzio R, Marquer D. 2006. Deformation and metamorphism at the eastern border of the Tenda massif (NE Corsica) a record of subduction and exhumation of continental crust. J. Struct. Geol. 28: 1748–1766.

Monié P, Torres-Roldán RL, García-Casco A. 1994. Cooling and exhumation of the Western Betic Cordilleras, 40Ar/39Ar thermochronological constraints on a collapsed terrane. Tectonophysics 238: 353–379.

Mora M. 1993. Tectonic and sedimentary analysis of the Huercal-Overa region, SE Spain, Betic Cordillera. Oxford (England): Oxford University, 300 p.

Morris A, Anderson A. 1996. First paleomagnetic results from the ECORS-Moroccan Trench region. Tectonophysics 258: 173–184.

Morris RG, Sinclair HD, Yelland AJ. 1998. Exhumation of the Pyrenean orogen: implications for sediment discharge. Basin Research 10: 69–85.

Moulin M, Klingelhoeffer F, Afiflado A, Aslanian A, Schnurle P, Nouzé H, et al. 2015. Deep crustal structure across a young passive margin from wide-angle and reflection seismic data (The SARDINIA Experiment) – I. Gulf of Lion’s margin. Bull. Soc. geol. France 186: 309–330.

Moutheau F, Filleaudeau PY, Vacherat A, Pik R, Lacombe O, Filledin J. 2006. Deformation and metamorphism at the eastern border of the Tenda massif (NE Corsica) a record of subduction and exhumation of continental crust. Tectonophysics 258: 173–184.

Müller RD, Sdrolias M, Gnaa C, Roest WR. 2008. Age, spreading rates, and spreading asymmetry of the world’s ocean crust. Geochim. Geophys. Geosyst. 9: Q04006. https://doi.org/10.1029/2007GC001743.

Munoz JA. 1992. Evolution of a continental collision belt: ECORS- Pyrenees crustal balanced cross-section. In: McClay KR, ed. Thrust Tectonics. London: Chapman and Hall, pp. 235–246.
Savelli M, Morillon AC, Bourgois J, Feraud G, Poupeau G, Saint-Sommaruga A. 1997. Geology of the central Jura and the Molasse Seton M, Muraldo MC, Spakman W, Chertova MV, van den Berg A, van Hinsbergen DJJ. 2004. A tomographic view on Western Scharf A, Handy MR, Favaro S, Schmid SM, Bertrand A. 2013. Scharf A, Handy MR, Favaro S, Schmid SM, Bertrand A. 2013. Sosson M, Maniscalco R, Grasso M. 2003. Pattern of orogenic rotations in central-eastern Sicily: implications for the timing of spreading in the Tyrrenian Sea. Journal of the Geological Society 160: 183–195. https://doi.org/10.1144/0016-764902-764043. Srivastava SP, Roest WP. 1989. Seaﬂoor spreading history II–IV, Map sheets L17–2-L17–6. In: Bell JS, ed. Atlantic Geoscience Centre, Geologic Survey of Canada. Stampﬁ G, Borel GD, Marchant RD, Molar J. 2002. Western Alps geological constraints on Western Tethyan reconstructions. In: Rosenbaum G, List G, eds. Reconstruction of the evolution of the Alpine–Himalayan orogen, pp. 77–106. Steinberger B, Torsvik TH. 2008. Absolute plate motions and true polar wander in the absence of hotspot tracks. Nature 452: 620–623. Sternai P, Jolivet L, Menant A, Gerya T. 2014. Subduction and mantle ﬂow driving surface deformation in the Aegean-Anatolian system. Earth Planet. Sci. Lett. 405: 105–118. https://doi.org/10.1016/j. epsl.2014.1008.1023. Stich D, Serpelloni E, de Lis Mancilla F, Morales J. 2006. Kinematics of the Iberia–Maghreb plate contact from seismic moment tensors and GPS observations. Tectonophysics 426: 295–317. Strzerynski P, Déverchère J, Cattaneo A, Domzig A, Yelles K, Mericier de Lépinay B, et al. 2010. Tectonic inheritance and Pliocene-Pleistocene inversion of the Algerian margin around Algiers: Insights from multibeam and seismic resection data. Tectonics 29: TC2008. https://doi.org/10.1029/2009TC002547. Tapponnier P. 1977. Evolution du système alpin en Méditerranée : poinçonnement et écrasement rigide-plastique. Bull. Soc. Geol. France 7(19): 437–460. Tapponnier P, Pelzger F, Dain AYL, Armijo R, Cobbold P. 1982. Propagating extrusion tectonics in Asia: new insights from simple experiments with plasticine. Geology 10: 611–616. Taymaz T, Jackson J, McKenzam D. 1991. Active tectonics of the north and central Aegean Sea. Geophys. J. Int. 106: 433–490. Teixell A, Labaume P, Ayarza P, Espurt N, de Saint Blanquat M, Lagabrielle Y. 2018. Crustal structure and evolution of the Pyrenean-Cantabrian belt: A review and new interpretations from recent concepts and data. Tectonophysics 724–725: 146–170. https://doi.org/10.1016/j.tecto.2018.1001.1009. Teson E, Pueyo EL, Teixell A, Barnolas A, Agusti J, Furri M. 2010. Magnetostatigraphic of the Ouazarzate Basin: Implications for the timing of deformation and mountain building in the High Atlas Mountains of Morocco. Geodinamica Acta 23: 151–165. https://doi.org/10.31166/ga.3123.3151-3165. Tozer RSJ, Butler RWH, Chiappini M, Corrado S, Mazzoli S, Speranza F, Maniscalco R, Grasso M. 2003. Pattern of orogenic rotations in central-eastern Sicily: implications for the timing of spreading in the Tyrrenian Sea. Journal of the Geological Society 160: 183–195. https://doi.org/10.1144/0016-764902-764043. Srivastava SP, Roest WP. 1989. Seaﬂoor spreading history II–IV, Map sheets L17–2-L17–6. In: Bell JS, ed. Atlantic Geoscience Centre, Geologic Survey of Canada. Stampﬁ G, Borel GD, Marchant RD, Molar J. 2002. Western Alps geological constraints on Western Tethyan reconstructions. In: Rosenbaum G, List G, eds. Reconstruction of the evolution of the Alpine–Himalayan orogen, pp. 77–106. Steinberger B, Torsvik TH. 2008. Absolute plate motions and true polar wander in the absence of hotspot tracks. Nature 452: 620–623. Sternai P, Jolivet L, Menant A, Gerya T. 2014. Subduction and mantle ﬂow driving surface deformation in the Aegean-Anatolian system. Earth Planet. Sci. Lett. 405: 105–118. https://doi.org/10.1016/j. epsl.2014.1008.1023. Stich D, Serpelloni E, de Lis Mancilla F, Morales J. 2006. Kinematics of the Iberia–Maghreb plate contact from seismic moment tensors and GPS observations. Tectonophysics 426: 295–317. Strzerynski P, Déverchère J, Cattaneo A, Domzig A, Yelles K, Mericier de Lépinay B, et al. 2010. Tectonic inheritance and Pliocene-Pleistocene inversion of the Algerian margin around Algiers: Insights from multibeam and seismic resection data. Tectonics 29: TC2008. https://doi.org/10.1029/2009TC002547. Tapponnier P. 1977. Evolution du système alpin en Méditerranée : poinçonnement et écrasement rigide-plastique. Bull. Soc. Geol. France 7(19): 437–460. Tapponnier P, Pelzger F, Dain AYL, Armijo R, Cobbold P. 1982. Propagating extrusion tectonics in Asia: new insights from simple experiments with plasticine. Geology 10: 611–616. Taymaz T, Jackson J, McKenzie D. 1991. Active tectonics of the north and central Aegean Sea. Geophys. J. Int. 106: 433–490. Teixell A, Labaume P, Ayarza P, Espurt N, de Saint Blanquat M, Lagabrielle Y. 2018. Crustal structure and evolution of the Pyrenean-Cantabrian belt: A review and new interpretations from recent concepts and data. Tectonophysics 724–725: 146–170. https://doi.org/10.1016/j.tecto.2018.1001.1009. Teson E, Pueyo EL, Teixell A, Barnolas A, Agusti J, Furri M. 2010. Magnetostatigraphic of the Ouazarzate Basin: Implications for the timing of deformation and mountain building in the High Atlas Mountains of Morocco. Geodinamica Acta 23: 151–165. https://doi.org/10.31166/ga.3123.3151-3165. Tozer RSJ, Butler RWH, Chiappini M, Corrado S, Mazzoli S, Speranza F. 2006. Testing thrust tectonic models at mountain fronts: where has the displacement gone? Journal of the Geological Society, London 163: 1–14. https://doi.org/10.1144/0016-764904-764140. Trotet F, Jolivet L, Vidal O. 2001. Tectono-metamorphic evolution of Syros and Sifnos islands (Cyclades, Greece). Tectonophysics 338: 179–206. van Hinsbergen DJJ, Schmid SM. 2012. Map view restoration of Aegean–West Anatolian accretion and extension since the Eocene. Tectonics 31: TC5005. https://doi.org/10.1029/2012TC003132. van Hinsbergen DJJ, Langereis CG, Meulenkamp JE. 2005. Revision of the timing, magnitude and distribution of Neogene rotations in the western Aegean region. Tectonophysics 396: 1–34. van Hinsbergen DJJ, van der Meer DG, Zachariasse WJ, Meulenkamp JE, 2006. Deformation of western Greece during Neogene clockwise rotation and collision with Apulia. Int J Earth Sci (Geol Rundsch) 95: 463–490. https://doi.org/10.1007/s00531-00047-00535.
van Hinsbergen DJJ, Dupont-Nivet G, Nakov R, Oud K, Panaiotu C. 2008. No significant post-Eocene rotation of the Moesian Platform and Rhodope (Bulgaria): Implications for the kinematic evolution of the Carpathian and Aegean arcs. Earth Planet Sci Lett 273: 345–358.

van Hinsbergen DJJ, Dekkers MJ, Bozkurt E, Koopman M. 2010a. Exhumation with a twist: Paleomagnetic constraints on the evolution of the Menderes metamorphic core complex, western Turkey. Tectonics 29: TC3009. https://doi.org/10.1029/2009TC002596.

van Hinsbergen DJJ, Dekkers MJ, Koç A. 2010b. Testing Miocene compressional shortening in the northern Rif (Chefchaouen, Morocco). J. Geodyn. 77: 22–38. https://doi.org/10.1016/j.jog.2013.1009.1006.

Warburton J. 1986. The ophiolite-bearing Schistes Lustrés nappe in Alpine Corsica: a model for the emplacement of ophiolites that have suffered HP/LT metamorphism. Geol. Soc. Am. Memoir 164: 313–331.

Weijermars R, Roep TB, Van den Eekhout B, Postma G, Kleverlaan K. 1985. Uplift history of a Betic fold nappe inferred from Neogene-Quaternary sedimentation and tectonics (in the Sierra Alhamilla and Almeria, Sorbas and Tabernas Basins of the Betis Cordilleras, SE Spain). Geol. en Mijnbouw 64: 397–411.

Wessel P, Kroenke LW. 2008. Pacific absolute plate motion since 145 Ma: An assessment of the fixed hot spot hypothesis. J. Geophys. Res 113: B06101. https://doi.org/10.1029/2007JB005499.

Vissers RLM, Platt JP. 2003. Dating high-grade metamorphism – Constraints from rare-earth elements in zircon and garnet. Contrib. Miner. Pet. 145: 61–74.

Vijlioti L, Kent DV. 1990. Paleomagnetic results of Tertiary

Vignaroli G, Faccenna C, Rossetti F, Jolivet L. 2008. Orogen-parallel extension and arc bending forced by slab tearing and toroidal flow at the junction between Alps and Apennines. Tectonophysics 450: 34–50. https://doi.org/10.1016/j.tecto.2007.1012.1012.

Vignaroli G, Faccenna C, Rossetti F, Jolivet L. 2009. Insights from the apennines metamorphic complexes and their bearing on the kinematics evolution of the orogen. In: van Hinsbergen DJJ, Edwards MA, Govers R, eds. Collision and collapse at the Africa-Arabia-Eurasia subduction zone. London: The Geological Society, pp. 235–256.

Villaseñor A, Chevrot S, Harnafi M, Gallart J, Pazos A, Serrano I, et al. 2015. Subduction and volcanism in the Iberia-North Africa collision zone from tomographic images of the upper mantle. Tectonophysics 663: 238–249.

Vine FJ, Matthews DH. 1963. Magnetic anomalies over oceanic ridges. Nature 199: 947–949.

Vissers RLM, Meijer PT. 2012. Mesozoic rotation of Iberia: Subduction in the Pyrenees? Earth-Science Reviews 110: 93–110.

Vitale Brovarone A, Herwartz D. 2013. Timing of HP metamorphism in the Schistes Lustrés of Alpine Corsica: New Lu-Hf garnet and lawsonite ages. Lithos 172-173: 175–191. https://doi.org/10.1016/j.lithos.2013.1003.1009.

Vitale S, Zaghloul MN, D’Assisi Tramparulo F, El Ouaraghi B. 2014. Deformation characterization of a regional thrust zone in the northern Rif (Chefchaouen, Morocco). J. Geodyn. 77: 22–38. https://doi.org/10.1016/j.jog.2013.1009.1006.

Vergés J, Fernàndez M. 2012. Tethys-Atlantic interaction along the Iberia-Africa plate boundary: The Betic-Rif orogenic system. Tectonophysics 579: 144–172. https://doi.org/10.1016/j.tecto.2010.1002.

Vergés J, Sábat F. 1999. Contrasts in the western Mediterranean kinematic evolution along a 1000 km transect, from Iberia to Africa. In: Durand B, Jolivet L, Horvath F, Séranne M, eds. The Mediterranean basins: Tertiary extension within the Alpine orogen. London: Geological Society, pp. 63–80.

Vergés J, Fernández M, Martínez A. 2002. The Pyrenean orogen: pre-, syn-, and post-collisional evolution. In: Rosenbaum G, Lister GS, eds. Reconstruction of the evolution of the Alpine-Himalayan orogen, pp. 57–76.

Vially R, Tremolières P. 1996. Geodynamics of the Gulf of Lions: implications for petroleum exploration. In: Ziegler P, Horvath F, Séranne M, eds. Paris, pp. 129–158.

Vigliotti L, Kent DV. 1990. Paleomagnetic results of Tertiary

Vissers RLM, Platt JP, Van der Wal D. 1995. Late orogenic extension of the Betic Cordillera and the Alboran domain: a lithospheric view. Tectonics 14: 786–803.

Vitale Brovarone A, Herwartz D. 2013. Timing of HP metamorphism in the Schistes Lustrés of Alpine Corsica: New Lu-Hf garnet and lawsonite ages. Lithos 172-173: 175–191. https://doi.org/10.1016/j.lithos.2013.1003.1009.

Vitale S, Zaghloul MN, D’Assisi Tramparulo F, El Ouaraghi B. 2014. Deformation characterization of a regional thrust zone in the northern Rif (Chefchaouen, Morocco). J. Geodyn. 77: 22–38. https://doi.org/10.1016/j.jog.2013.1009.1006.

Warburton J. 1986. The ophiolite-bearing Schistes Lustrés nappe in Alpine Corsica: a model for the emplacement of ophiolites that have suffered HP/LT metamorphism. Geol. Soc. Am. Memoir 164: 313–331.

Weijermars R, Roep TB, Van den Eekhout B, Postma G, Kleverlaan K. 1985. Uplift history of a Betic fold nappe inferred from Neogene-Quaternary sedimentation and tectonics (in the Sierra Alhamilla and Almeria, Sorbas and Tabernas Basins of the Betis Cordilleras, SE Spain). Geol. en Mijnbouw 64: 397–411.

Wessel P, Kroenke LW. 2008. Pacific absolute plate motion since 145 Ma: An assessment of the fixed hot spot hypothesis. J. Geophys. Res 113: B06101. https://doi.org/10.1029/2007JB005499.

Westernman DS, Dini A, Innocenti F, Rocchi S. 2004. Rise and fall of a nested Christmas-tree laccolith complex, Elba Island, Italy. In: Breitkreuz C, Petford N, eds. Physical Geology of High Level Magmatic Systems. London: Geological Society, pp. 195–213.

Whitehouse MJ, Platt JP. 2003. Dating high-grade metamorphism – Constraints from rare-earth elements in zircon and garnet. Contrib. Miner. Pet. 145: 61–74.

Wijbrans JR, McDougall I. 1988. Metamorphic evolution of the Attic Cycladic Metamorphic Belt on Naxos (Cyclades, Greece) utilizing 40Ar/39Ar age spectrum measurements. J. Metamorph. Geol. 6: 571–594. https://doi.org/10.1111/j.1525-1314.1988.tb00441.x.

Wijbrans JR, van Wees JD, Stephenson RA, Cloetingh SAPL. 1993. Pressure-temperature-time evolution of the high-pressure-metamorphic complex of Sifnos, Greece. Geology 21: 443–446.

Williams JR, Platt JP. 2018. A new structural and kinematic framework for the Alborán Domain (Betic-Rif arc, western Mediterranean orogenic system). Journal of the Geological Society. https://doi.org/10.1144/jgs2017-086.

Wilson M, Bianchini G. 1999. Tertiary-Quaternary magmatism within the Mediterranean and surrounding regions. In: Durand B, Jolivet L, Horvath F, Séranne M, eds. The Mediterranean Basins: Tertiary extension within the Alpine Orogen, pp. 141–168.

Wortel MJR, Spakman W. 1992. Structure and dynamic of subducted lithosphere in the Mediterranean. Proc. Kon. Ned. Akad. v. Wetensch. 95: 325–347.

Wortel MJR, Spakman W. 2000. Subduction and slab detachment in the Mediterranean-Carpathian region. Science 290: 1910–1917.

Zarki H, Macaire JJ, Beck C, De Luca P. 2004. Morpho-sedimentary evolution of the lower Mouloya (North Eastern Morocco) during middle and upper Holocene. Seismicity and neotectonic effects. Geodinamica Acta 17: 205–217. https://doi.org/10.2136/ ga.3117.3205-3217.

Zeck HP, Williams IS. 2001. Hercynian metamorphism in nappe core complexes of the Alpine Betic-Rif belt, Western Mediterranean – a SHRIMP zircon study. Journal of Petrology: 42: 1373–1385.

Zeck HP, Albaf H, Hansen BT, Torres-Roldán RL, García-Casco A, Martin-Algarra A. 1989. A 21 ± 2 Ma age for the termination of the
ductile Alpine deformation in the internal zone of the Betic Cordilleras, South Spain. *Tectonophysics* 169: 215–220.

Zeck HP, Monié P, Villa IM, Hansen BT. 1992. Very high rates of cooling and uplift in the Alpine Belt of the Betic Cordilleras, Southern Spain. *Geo-Marine Letters* 20: 79–82.

Ziegler P. 1999. Evolution of the Arctic-North Atlantic and the Western Tethys. *AAPG Memoir* 43: 164–196.

Zitellini N, Ranero CR, Loreto MF, Ligi M, Pastore M, D’Oriano P, et al. 2019. Recent inversion of the Tyrrhenian Basin. *Geology* 48: 123–127. https://doi.org/10.1130/G46774.46771.

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