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Extensional crustal tectonics and crust-mantle coupling, a view from the geological record

Laurent Jolivet[a,*], Armel Menant[b], Camille Clerc[c], Pietro Sternai[d], Nicolas Bellahsen[a], Sylvie Leroy[a], Raphaël Pik[e], Martin Stab[e], Claudio Faccenna[f], Christian Gorini[a]

[a] Sorbonne Université, CNRS-INSU, Institut des Sciences de la Terre Paris, ISTeP UMR 7193, F-75005 Paris, France
[b] IPGP, Tectonique et Mécanique de la Lithosphère, Paris, France
[c] LIVE – Université de la Nouvelle Calédonie - BPR4 – 98851, Nouméa, Cedex, France
[d] Department of Earth Sciences, University of Geneva, Switzerland
[e] CRPG UMR 7358 CNRS, Université de Lorraine, Nancy, France
[f] Dip. Scienze, Università Roma TRE, Rome, Italy

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ABSTRACT

We present here a number of geological observations in extensional contexts, either continental rifts or back-arcs, that show different situations of potential coupling between asthenospheric flow and crustal deformation. Several of these examples show a deformation distributed over hectometre to kilometre thick shear zones, accommodated by shallow dipping shear zones with a constant asymmetry over large distances. This is the case of the Mediterranean back-arc basins, such as the Aegean Sea, the northern Tyrrhenian Sea, the Alboran domain or the Gulf of Lion passive margin. Similar types of observation can be made on some of the South Atlantic volcanic passive margins and the Afar region, which were formed above a mantle plume. In all these examples the lithosphere is hot and the lithospheric mantle thin or possibly absent. We discuss these contexts and the main controlling parameters for this asymmetrical distributed deformation that implies a simple shear component at the scale of the lithosphere. These parameters include an original heterogeneity of the crust and lithosphere (tectonic heritage), lateral density gradients and contribution of the underlying asthenospheric flow through basal drag or basal push. We discuss the relations between the observed asymmetry and the direction and sense of the mantle flow underneath. The chosen examples suggest that two main mechanisms can explain the observed asymmetry: (1) shearing parallel to the Moho in the necking zone during rifting and (2) viscous coupling of asthenospheric flow and crustal deformation in back-arc basins and above plumes. Slipping along pre-existing heterogeneities seems a second-order phenomenon at lithospheric or crustal scale.

1. Introduction

Deformation of continents, mountain building or rifting, is mainly understood as resulting from interactions between plates and transmission of stress across plate boundaries (Dewey and Bird, 1970). The asymmetry of most mountain belts is a direct consequence of the asymmetry of subduction zones, oceanic or continental, where the subducting plate sinks below the overriding plate (Faccenna et al., 2013a). In extensional settings, the asymmetry of deformation is less obvious to explain, as plate divergence is essentially a symmetrical process. Strain localisation along a few major shallow-dipping shear zones (Wernicke, 1985) is one solution to render the pattern of deformation asymmetrical at crustal or lithospheric scale, but it was shown that such shear zones usually do not cross the entire lithosphere; they are instead often restricted to the upper and middle crust (Klemperer, 1988). Moreover, when the lithosphere is weakened by a high heat flow, such a localized deformation in the lower crust and mantle is not likely. An alternative solution is that shear stresses are transmitted from the flowing asthenosphere up to the crust of the overlying lithospheric plate. We explore in this paper several cases of asymmetric extensional deformation, either in classical rifting contexts or in back-arc environments. We summarize recent findings on several types of extensional contexts such as the Mediterranean back-arc basins, the South Atlantic passive margins and the Afar region, where the lithosphere is thin and hot and shows asymmetrical finite geometries at crustal scale over vast regions, implying a component of simple shear at the scale of the lithosphere, and we discuss the causes of this simple shear component transmitted across the entire crust, proposing the

* Corresponding author.
E-mail address: laurent.jolivet@sorbonne-universite.fr (L. Jolivet).

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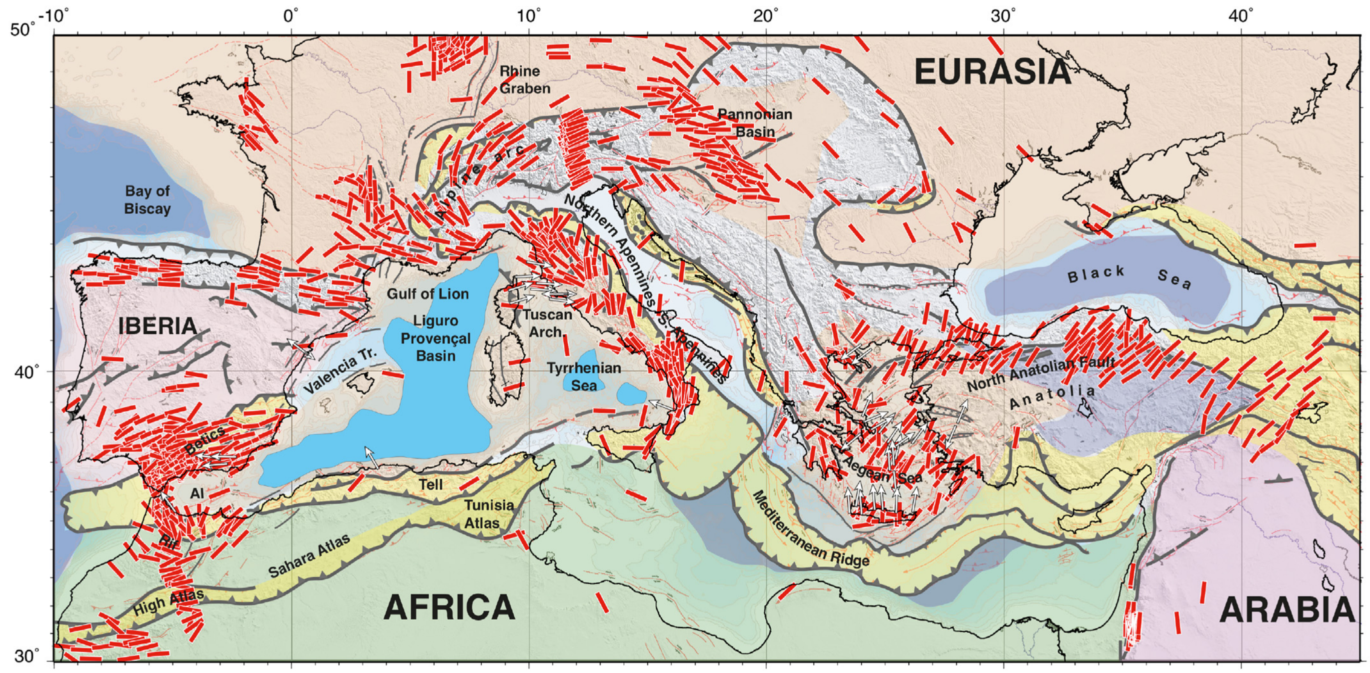

Fig. 1. Tectonic map of the Mediterranean realm and a compilation of SKS-waves seismic anisotropy after Faccenna et al. (2014).

possible active role of the underlying mantle flow.

2. Mediterranean back-arc basins

Mediterranean back-arc basins have formed since the Early Oligocene above the retreating subduction of the African plate below Eurasia (Le Pichon and Angelier, 1981; Malinverno and Ryan, 1986; Royden, 1993; Jolivet and Faccenna, 2000; Agostini et al., 2010; Carminati et al., 2012) (Fig. 1). At the time of the first retreat, the overriding plate of these subductions was almost everywhere occupied by a mountain belt born from the accretion of African or Apulian crustal units (Bonneau and Kienast, 1982; Jolivet et al., 2003; van Hinsbergen et al., 2005a; Jolivet and Brun, 2010; Ring et al., 2010). The crust below these mountain belts was thus thick and mostly made of upper crustal material, metamorphic basement and metasediments (Le Pichon et al., 1988). When slab retreat started, the cold slab was replaced by hot asthenosphere and the deep parts of the thick crustal wedge, formed within the subduction channel in high pressure-low temperature (HP-LT) conditions, were heated and entered the field of partial melting (Vanderhaeghe and Teyssier, 2001; Jolivet and Brun, 2010). Depending on the amount of finite extension and the timing of exhumation, metamorphic core complexes (MCCs) were exhumed with variable retrograde P-T evolution (Jolivet et al., 2003; Jolivet and Brun, 2010; Ring et al., 2010; Labrousse et al., 2016).

The Aegean Sea (Fig. 2), for instance, shows an evolution from "cold" MCCs that preserve relatively well the HP-LT parageneses to "hot" MCCs cored with migmatites (Jolivet et al., 2004; van Hinsbergen et al., 2005b; Huet et al., 2011). Detailed studies of the kinematics of extension, both of ductile deformation below detachments and brittle deformation above, show coherent patterns over vast regions (Jolivet et al., 1994a; Jolivet, 2001; Jolivet et al., 2013). Moreover, the kinematic pattern recorded in the exhumed MCCs is fully compatible with the mantle stretching direction as shown by SKS waves anisotropy (Kreemer et al., 2004; Jolivet et al., 2009) (Fig. 1). Two examples are summarized here.

2.1. The aegean domain

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Extension in the Aegean domain developed in the back-arc region of the Hellenic subduction zone from the Eocene to the Present (Figs. 2 and 3). In a first period, it was localized in the Rhodope Massif during the Eocene and then migrated in the Aegean Sea and Menderes Massif after the Late Eocene (Jolivet et al., 1994a, 2004; Brun and Faccenna, 2007; Brun and Faccenna, 2007; Jolivet and Brun, 2010; Ring et al., 2010). The history of magmatism shows that during the first period, the magmatic arc was initially limited to the Balkans and Rhodope, while it subsequently migrated at 2–3 cm/yr toward the south, suggesting that slab retreat was faster (Jolivet et al., 2004; Menant et al., 2016a), which is compatible with the thinner crust observed in the Aegean Sea (Tirel et al., 2004). Several metamorphic core complexes were exhumed during these two distinct phases, including the Rhodope Massif itself and the different MCCs of the Cyclades (Fig. 2, Fig. 3) (Lister et al., 1984; Urai et al., 1990; Gautier et al., 1993; Gautier and Brun, 1994; Jolivet et al., 2004; Brun and Sokoutis, 2007; Menant et al., 2016a). The direction of stretching seen in these MCCs follows a simple pattern (Fig. 2) (Jolivet et al., 1994a; Jolivet 2001, Jolivet et al., 2010a; Brun and Sokoutis, 2010; Grasemann et al., 2012; Jolivet et al., 2013). The sense of shear is top-to-the SW in the Rhodope (Brun and Faccenna, 2007) and top-to-the NE or N in most of the Cyclades (Jolivet et al., 2013), except in the southwest where the sense of shear is top-to-the south (Grasemann and Petrakakis, 2007; Grasemann et al., 2012).

Extension in the Rhodope is mainly accommodated by a few southwest-dipping detachments, such as the Kerdylion Shear Zone (Wawrzenitz and Krohe, 1998; Brun and Sokoutis, 2007; Burg, 2012). The whole massif was exhumed as a single, large core complex and the width of the present-day outcropping area of the MCC corresponds approximately to the displacement along the main detachment (~150 km) during top-to-the southwest shearing. This Eocene extension was coeval with the formation and exhumation of the Cycladic Blueschists further to the south.

Extension in the Cyclades is taken up by a few large-scale structures such as the North Cycladic Detachment System (NCDS) (Jolivet et al., 2010b), the Naxos-Paros Extensional Fault System (NPEFS) (Urai et al., 1990; Gautier et al., 1993; Vanderhaeghe, 2004; Seward et al., 2009; Bargnesi et al., 2013) or the West Cycladic Detachment System (WCDS) (Grasemann and Petrakakis, 2007; Iglseder et al., 2011; Grasemann et al., 2012; Rice et al., 2012). During the same Oligo-Miocene period,

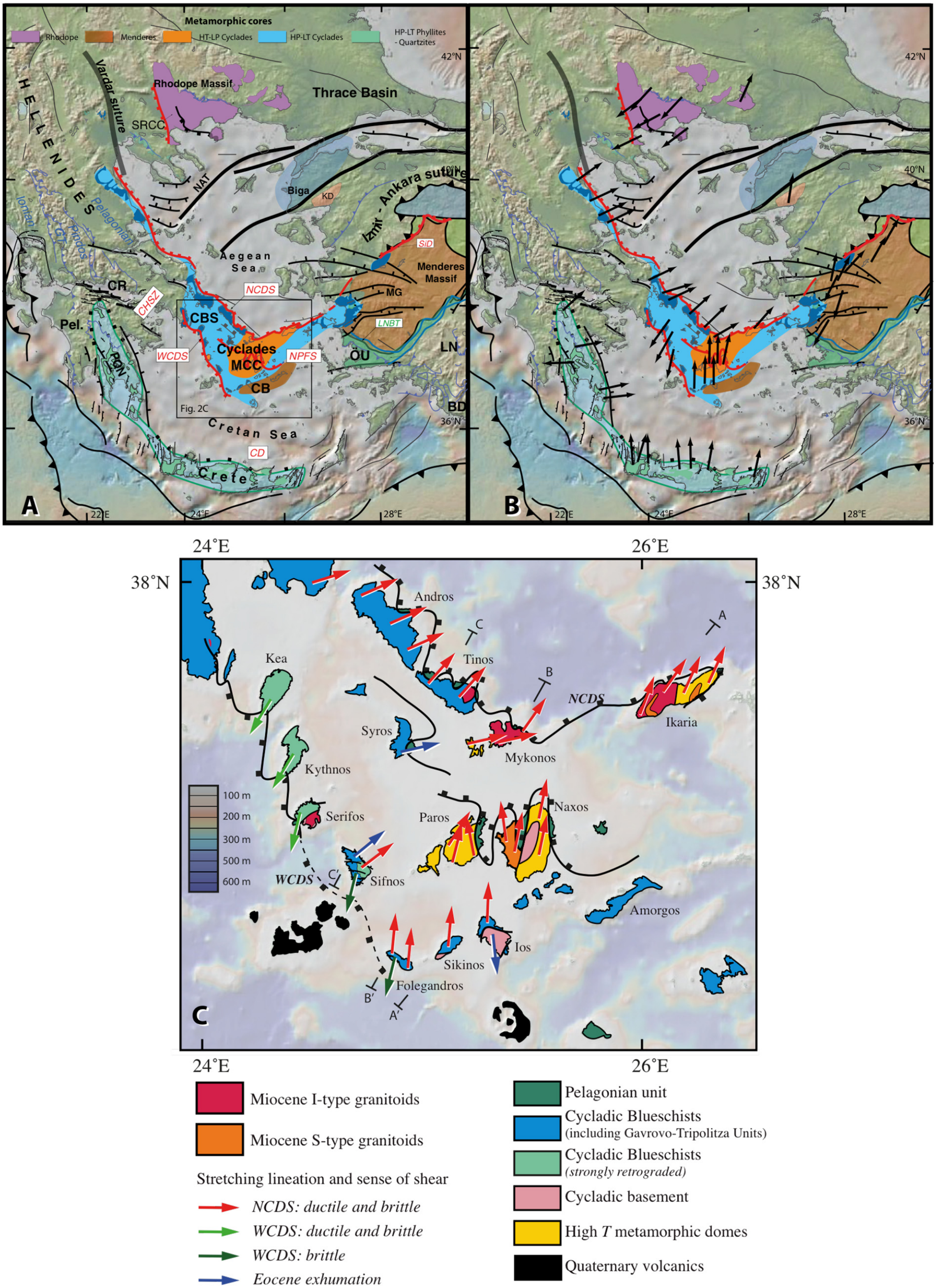

Fig. 2. Tectonics of the Aegean region. A: The main metamorphic core complexes and detachments. B, stretching lineations and sense of shear, after Jolivet et al. (2013). Lineations shown here are only those related to post-orogenic extension: Eocene and Oligo-Miocene in the Rhodope, Oligo-Miocene in the Cyclades and Crete. C: Detailed tectonic map of the Cyclades archipelago and stretching lineations and kinematic indicators, after Jolivet et al. (2015b).CD: Cretan Detachment, CHSZ: Central Hellenic Shear Zone, NCDS: North Cycladic Detachment System, NPEFS: Naxos-Paros Extensional Fault System, SD: Simav Detachment, WCDS: West Cycladic Detachment System. AA', BB' and CC': location of cross-sections displayed in Fig. 3B, C and D.

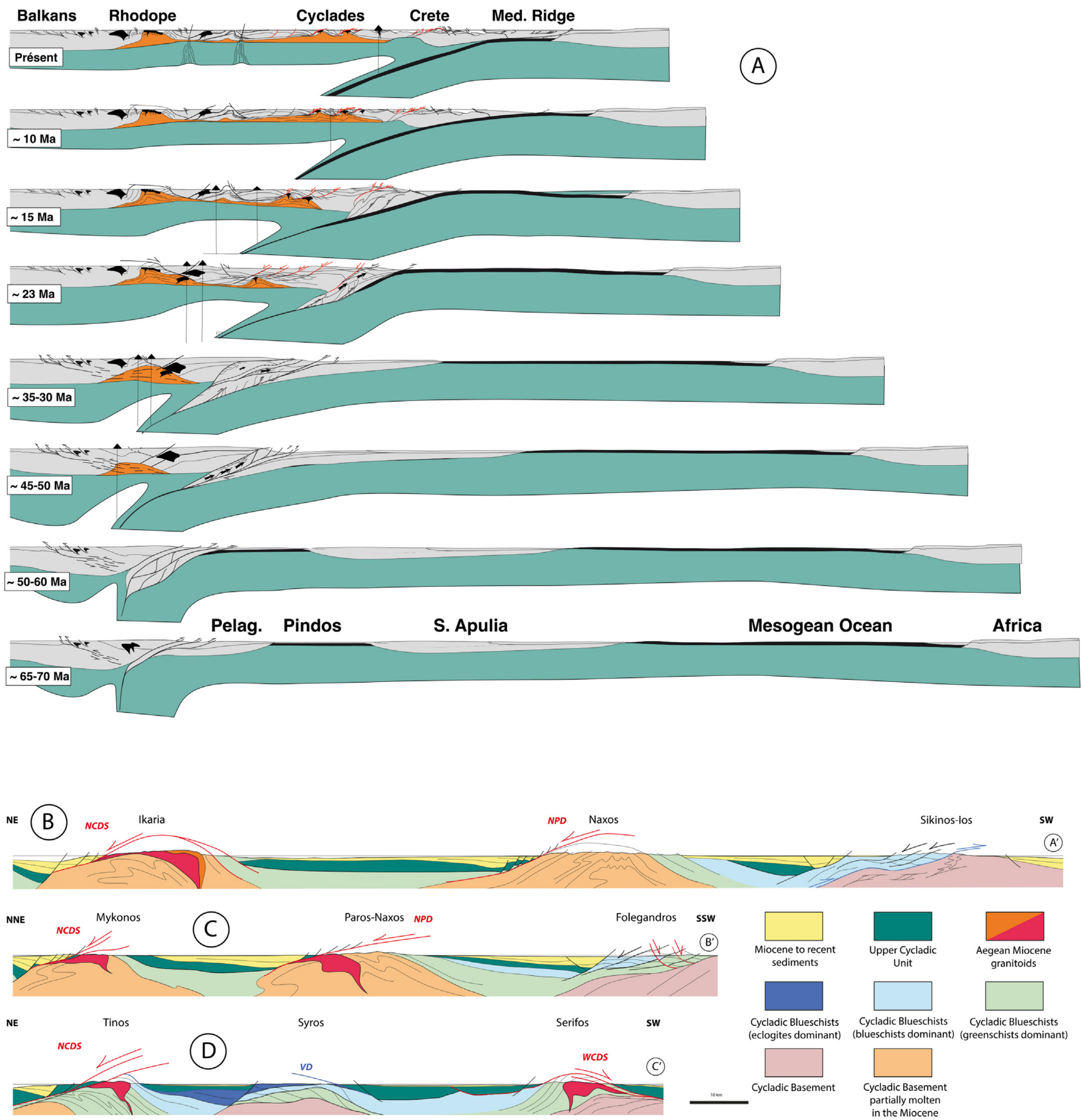

Fig. 3. Cross-sections of the Aegean domain. A: Evolution of the Aegean domain along a N—S section from the Balkans to the northern margin of Africa, from Jolivet and Brun, 2010. B, C and D: three cross-sections across the Cyclades (see location on Fig. 2C), from Jolivet et al. (2015b).

the HP-LT units of Crete were exhumed below a north-dipping detachment system (the Cretan Detachment) with a similar top-to-the north sense of shear (Fassoulas et al., 1994; Jolivet et al., 1994b, 1996; Seidel et al., 2007). The Cretan Detachment accommodated the exhumation of the metamorphic units of Crete just north of the Oligo-Miocene subduction zone and during the formation of the Aegean Sea. The Cretan Detachment accommodated the formation of asymmetrical (half-graben geometry) sedimentary basins in the upper plate during the Early Miocene (Jolivet et al., 1996; Seidel et al., 2007) and it roots within the thinned crust of the Cretan Sea. In this case the respective amounts of exhumation related to subduction channel dynamics (syn-orogenic exhumation, Jolivet et al., 2003) and that related to back-arc extension (post-orogenic extension) is not easy to separate as the same detachment was accommodating the deformation. The case of the Northern Cyclades is relatively simpler because the NCDS (post-orogenic, Oligo-Miocene) is a different structure from the Vari Detachment (syn-orogenic, Eocene, with a minor later brittle reactivation). Syn-orogenic exhumation took the Cycladic Blueschists Unit from the depth of the eclogite facies (22 kbar) to the depth of the blueschists facies (9 kbar) in the Eocene and post-orogenic exhumation then brought the same unit to the surface in the Oligocene and Miocene (Parra et al., 2002; Laurent et al., 2018). Syn-orogenic exhumation can also be accommodated by the extrusion of a wedge such as in the example of Evia (Xypolias et al., 2012) but in this case too, a detachment is required to explain the pressure gap on either side of the main contact at the top of the Cycladic Blueschists.

Along the transect that has accommodated most of extension, i.e. in the centre and east of the Aegean domain (from Mykonos, to Naxos and Crete), the sense of ductile and brittle shear is always top-to-the north or northeast (Jolivet et al., 2015b) (Fig. 2, Fig. 3). Laterally, in the western part of the Aegean Sea or the Menderes Massif, systems of detachments are less asymmetrical. The Menderes Massif has probably been first exhumed from below a north-dipping low-angle normal fault, the Simav Detachment (van Hinsbergen, 2010; Bozkurt et al., 2011), a possible extension of the NCDS (Jolivet et al., 2010b). More recent detachments, observed within the Massif, are either north-dipping (the Gediz-Alasehir Detachment) or south-dipping (Büyük Menderes Detachment) (Bozkurt and Park, 1994; Hetzel et al., 1995; Bozkurt and Oberhänsli, 2001; Lips et al., 2001). The western Cyclades have been unroofed below the southwest-dipping WCDS (Grasemann et al., 2012), dipping opposite to the NCDS. Although it is difficult to precisely quantify the respective full amounts of slip (ductile and brittle) on these two detachments (Brichau et al., 2006, 2007, 2008, 2010), it seems clear that the system is less asymmetrical than in the central region where all detachments dip northward and all kinematic indicators point northward.

A point of discussion arises about the island of Ios (Fig. 2). The main shear zone on this island, between the Cycladic Blueschists and the Cycladic Basement, has been first interpreted as a detachment with a top-to-the south sense of shear (Lister et al., 1984; Vandenberg and Lister, 1996; Foster and Lister, 2009). Later, Huet et al. (2009), based on new field observations, suggested that the dome-shaped contact is essentially a thrust formed in high-pressure and low-temperature conditions with top-to-the south shear sense, later reworked by top-to-the north shearing along distributed north-dipping shear zones related to back-arc extension. More recently, Mizera and Behrmann (2015) studied the distribution of shear zones in the basement and concluded that the top-to-the south detachment model is preferable although the contact had originally been a thrust. They further suggested that the deformation of the gneissic basement involves a significant component of coaxial stretching (approximately 70% N—S crustal stretching and up to 40% subvertical shortening in a plane strain environment) and a minor top-to-the south shearing. The upward gradient of strain leads them to choose the extension model. The same upward strain gradient was interpreted by Huet et al. (2009) as witnessing a major shear zone, and the observation of preserved *syn*-high pressure top-to-the south kinematic indicators associated with HP-LT parageneses in the overlying Cycladic Blueschists at close proximity to the contact was then taken as an indication of a syn-HP thrust. Besides, cooling ages do not show a significant contrast between the footwall and hanging-wall of this contact (Laurent et al., 2017). If the contact were a detachment and the footwall a metamorphic core complex, ages in the lower unit should be younger, which is not observed. We thus stick to the earlier interpretation of Huet et al. (2009) of a major Eocene top-to-the south thrust remobilized in the Oligocene and Miocene by a north-directed extensional shearing. If our interpretation is correct, the West Cycladic Detachment System (WCDS) would die out east of Serifos (Fig. 2C) and be only expressed as south-dipping brittle normal faults visible on the islands of Folegandros (Augier et al., 2015) and Sifnos (Ring et al., 2011; Roche et al., 2016).

At the scale of the Aegean region, extension was thus first asymmetrical with one major MCC exhumed below a top-to-the SW detachment (the Rhodope in the Eocene) and then asymmetric with a top-to-the north or top-to-the NE in the centre of the Aegean Sea (The Cyclades in the Oligo-Miocene) (Fig. 4). The high-temperature core complexes, characterized by amphibolite-facies metamorphism and migmatites, of the central and eastern parts of the extended domain, from the central Cyclades to the Menderes Massif show that the heat flow was high during Oligo-Miocene extension and that the lithospheric mantle was probably very thin. Conjugate detachments are observed in the west and east where finite extension is less intense. It is noticeable that the recent activity of the Corinth Rift also involves a component of top-to-the north shearing along a shallow north-dipping decollement at the brittle-ductile transition (Rigo et al., 1996; Sorel, 2000; Flotté et al., 2005; Jolivet et al., 2010a).

This asymmetry should now be explained. One could propose that the Eocene thrusts were formed with a southward propagation and northward dip and that they have simply been reactivated during extension. This could certainly be part of the truth but the example of the Corinth Rift which trends at almost 90° on the earlier compressional structures pleads against this solution. We will see in the following that the example of the Northern Tyrrhenian Sea is also at odds with this proposal.

A point of discussion should be introduced at this stage as we will use the same approach with the next examples. We have assumed above that the presence of a majority of north- or northeast-dipping low-angle faults and shear zones (the detachments) calls for a component of simple shear at crustal or lithospheric scale. It is a general challenge to decipher in a deformed geological object the respective components of pure and simple shear. Our main concern here is the existence of a component of simple shear at large scale. Detailed studies of the vorticity at sample or outcrop-scale can help deciphering the relative importance of simple and pure shear. The reader is invited to see a review of these methods by Xypolias (2010). But this sort of detailed approach becomes difficult at large-scale. The way we proceed here is identifying the large-scale discontinuities (the main detachments) and assessing the sense of motion and, when possible, the amount of displacement (together with its age and P-T conditions). This approach led to the discovery of the North Cycladic Detachment System (Gautier and Brun, 1994; Jolivet et al., 2010b), while Grasemann et al. (2012), with a similar approach discovered the West Cycladic Detachment System, or others reported the Paros-Naxos Detachment (Urai et al., 1990; Gautier et al., 1993; Bargnesi et al., 2013). The main approach is to map the stretching lineations and relative strain intensity (to identify strain gradients – shear zones) and see whether we observe a systematic orientation and sense of shear. This approach ensures that a certain component of simple shear is present at the scale of a MCC (say one Cycladic island for instance). This does not mean that there is no component of pure shear, which is almost surely always present but impossible to quantify at crustal scale. Then the presence of a strong pressure and temperature gap across the detachment and the localization of deformation along it also mean that a large displacement has been accommodated along the low-angle fault or the shear zone (several tens of kilometres), which already implies a significant component of simple shear. The last step is to map these kinematic indicators at the scale of several hundreds of kilometres. The observation then is that the sense of shear is constant over a large part of the Aegean Sea, accommodated by large-scale localized structures, which we interpret as an indication that the strain is asymmetrical at crustal and lithospheric scale (Jolivet et al., 2009; 2013).

It should also be noted here that some of these deformations have been differently interpreted, calling for a larger part of deformation within the subduction channel instead of below extensional detachments coeval with the formation of the Aegean Sea. Part of the deformation observed within the Aegean metamorphic core complexes was indeed accommodated in the subduction zone and not during back-arc extension (Trotet et al., 2001; Ring et al., 2007; Xypolias, 2010; Laurent et al., 2016). But it remains that a large part of this deformation is more recent, as shown by the deformation of coeval Miocene granitoids in Tinos, Mykonos or Ikaria, and the continuum of deformation before, during and after these intrusives were emplaced in the crust (Faure et al., 1991; Grasemann and Petrakakis, 2007; Beaudoin et al., 2015; Laurent et al., 2015; Rabillard et al., 2015; 2018; Bessière et al., 2017). These cannot be related to the subduction channel and they are

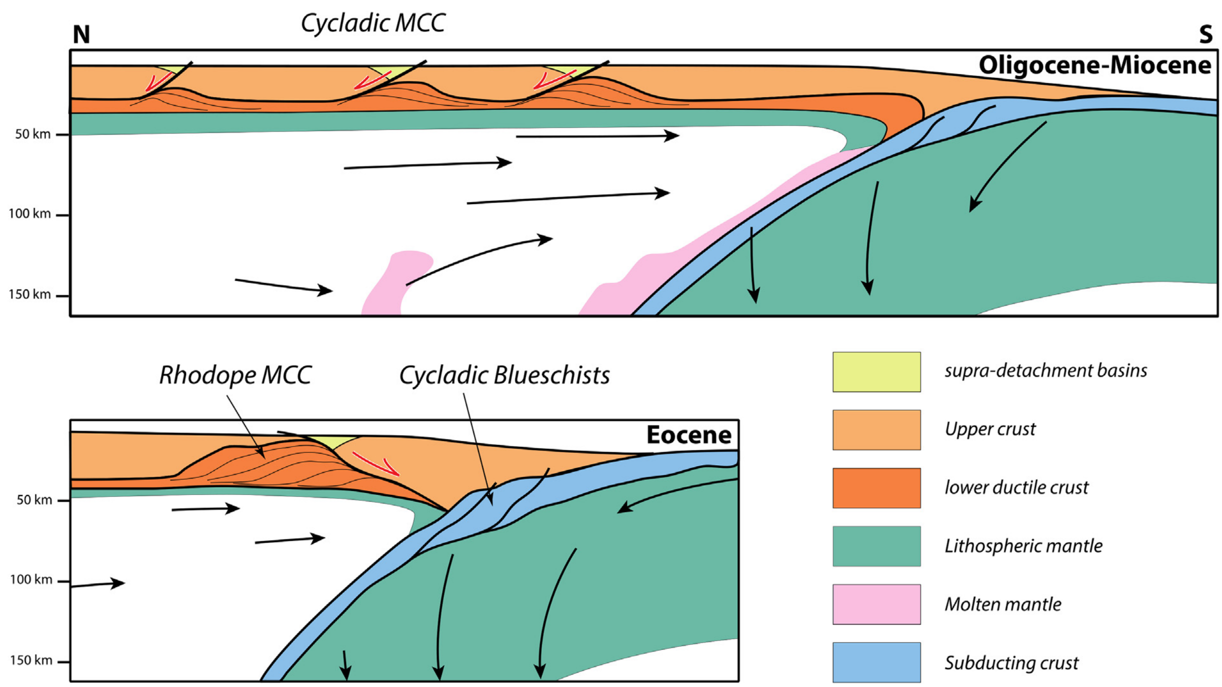

Fig. 4. Schematic cross-sections across the Aegean domain in the Eocene and the Oligo-Miocene showing the main active MCCs and detachments.

also coeval with the formation of basins. Radiometric ages and low-temperature thermochronology also show that a large part of this deformation is recent and thus extensional (Parra et al., 2002; Kumerics et al., 2005; Brichau et al., 2006, 2007, 2008; Laurent et al., 2017). We thus consider that a large part of the deformation seen below the main Aegean detachments is extensional and relates to the formation of the Aegean Sea.

2.2. Northern Tyrrhenian Sea

The Northern Tyrrhenian Sea also shows a series of low-angle normal faults (LANF) and metamorphic core complexes, from Alpine Corsica in the west to the Apennines in the east (Réhault et al., 1984; Jolivet et al., 1998) (Fig. 5). Extension started in the Early Oligocene with the rifting of the Liguro-Provençal Basin and migrated eastward until the Present, coeval with a migration of magmatism is observed (Jolivet et al., 1998). From Alpine Corsica eastward, at variance with the Aegean Sea case, most detachments dip toward the trench (Fig. 6, Fig. 7), when the main thrusts that built the Apennines dip westward (Fig. 6). A clear eastward migration of the locus of extension, coeval with a migration of magmatism is observed (Jolivet et al., 1998).

In Corsica, from the Oligocene to the Middle Miocene, the East Tenda Shear Zone (ETSZ) has reactivated the earlier thrust contact between the Schistes Lustrés Nappe in the east and the Tenda Massif in the west (Daniel et al., 1996; Rossetti et al., 2015; Beaudoin et al., 2017). This contact was active in HP-LT conditions at the time of top-to-the west thrusting (Eocene) and was reactivated during exhumation from blueschist-facies to greenschist-facies conditions and finally reaching the brittle domain during top-to-the east extensional shearing (Fournier et al., 1991; Jolivet et al., 1998; Molli et al., 2006; Rossetti et al., 2015; Beaudoin et al., 2017). Radiometric ages of *syn*-kinematic micas of the ESTZ show that ductile deformation continued until 25 Ma ($^{40}Ar/^{39}Ar$) and even 22–21 Ma (Rb/Sr) (Brunet et al., 2000; Rossetti et al., 2015). This extension has controlled the deposition and tilt of a sedimentary basin from the Oligocene to the Middle Miocene. Other contacts were also reactivated by this Oligo-Miocene extension. The Alpine thrusts in the region of Corte further south were also reactivated by brittle low-angle normal faults dipping to the east (Jolivet et al., 1991). The exhumation of the Cap Corse Schistes Lustrés was controlled by a major east-dipping low-angle detachment that crops out well near the northernmost tip of Cap Corse. Several contacts between tectonic units within the Schistes Lustrés were also reactivated during top-to-the east shear (Fournier et al., 1991; Jolivet et al., 1991). So, in Alpine Corsica the reactivation of a former thrust is compatible with the observed tectono-metamorphic evolution. But this is no longer true to the east, from the Tuscan Archipelago to Apennines.

Indeed, east of Corsica, the main compressional structures show an eastward vergence, from Elba Island to the front of the Apennines, while later extensional structures dip toward the east and cut the earlier thrusts. Several metamorphic core complexes capped by top-to-the east detachments have been described on the islands of Elba and Giglio (Keller and Pialli, 1990; Daniel and Jolivet, 1995; Jolivet et al., 1998; Rossetti et al., 1999; Collettini and Holdsworth, 2004). They were formed coeval with the emplacement of intrusions of granodiorites during the Late Miocene and Early Pliocene. Similar features were described also in Tuscany and east-dipping low-angle normal faults are now active in the Apennines such as the Alto Tiberina Fault (Boncio et al., 2000; Collettini and Barchi, 2004; Brozzetti et al., 2009; Collettini et al., 2009).

One of the main differences with the Aegean Sea case is that extension in the Northern Tyrrhenian Sea and the Apennines shows a clear eastward migration with extension active during a relatively short time in a given place, while the whole central Aegean seemed to be active roughly at the same time. This suggests that the Northern Tyrrhenian crust was more resistant and more prone to localize strain than the Aegean crust. Another first-order difference is the sense of shear toward the trench. In that case the low-angle normal faults dip opposite to the former thrusts that constructed the Apennines orogenic wedge and they cut through them instead of simply reactivating them. Reactivation in this case cannot explain the observed sense of shear, except in the west along the former Alpine thrust front reactivated by the ETSZ.

One additional geodynamic constraint should be considered. The motions of global plates includes a component of rigid rotation about a pole located at high latitudes that broadly translates into an eastward motion with respect to the asthenosphere, or to a westward motion of the asthenosphere with respect to the lithosphere (Ricard et al., 1991). Doglioni et al. (Doglioni et al., 2007; Doglioni and Panza, 2015) use this

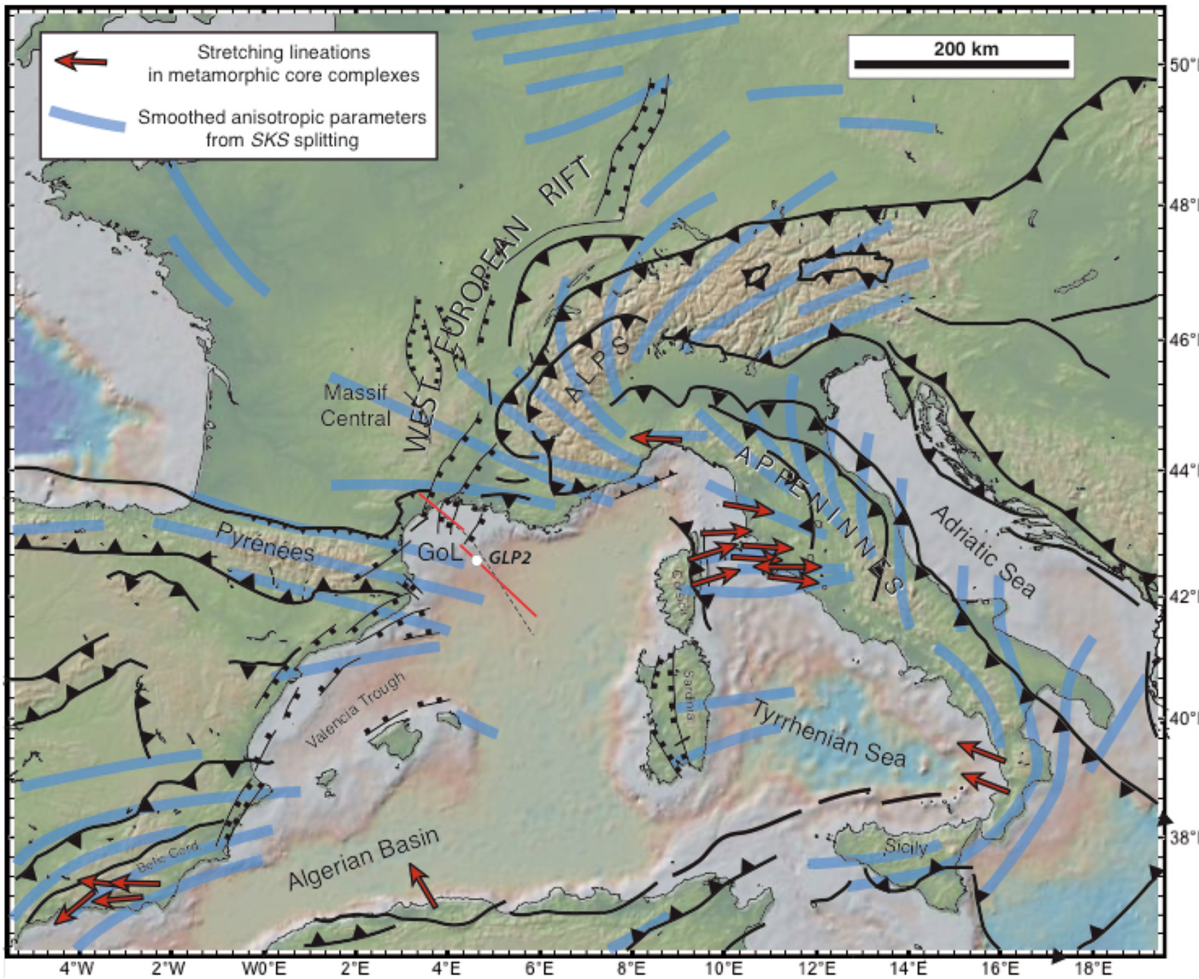

Fig. 5. Tectonic map of the Western Mediterranean region showing the main faults and shear zones and their kinematic indicators as well average directions of SKS-wave anisotropy fast directions (Jolivet et al., 2009). Red line is the trace of the Gulf of Lion profile shown on Fig. 7C and D. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

global rotation argument to discuss the polarization of plate tectonics and especially a different behaviour of subduction zones, whether slabs sink in the direction of this mantle flow or opposed to it. This leads to steeply or shallow-dipping slabs. One of the examples put forward by these authors is the opposition of direction and style of the Hellenic and Apennines subduction zones. The Apennines slab is steep because it dips SW-ward while the Hellenic slab below the Aegean Sea is shallower because it dips toward the north. The consequences on upper plate deformation are however not entirely clear. Slabs dipping in the direction of this global asthenospheric flow are found below overriding plates deformed in compression (the Andes) or in extension (the Aegean Sea). The reason is probably that slab motion is controlled by other causes such as their own density contrast (slab retreat, slab tearing, slab detachment) with the asthenosphere or large-scale mantle convection and that these movements are often faster than the global component of plate rotation. Although we acknowledge that the global rotation may have some significant influence on the dip of slab, we consider that it is not the main driver of back-arc dynamics.

2.3. Gulf of Lion

During the rifting of the Liguro-Provençal Basin, the continental margin of the Gulf of Lion was formed on the northwestern side (Fig. 7B). Since the eighties, this margin had posed a number of questions pertaining to the apparent incompatibility between the amounts of thinning deduced from crustal thickness on the one hand and from observed normal faults on the other hand (Burrus, 1984; De Voogd et al., 1991; Gorini et al., 1994; Séranne et al., 1995; Séranne, 1999). The few normal faults seen on the profiles cannot account for the quite large thinning factor at crustal scale. The answer lies in depth-dependent extension, as suggested by an industrial reflection profile across the margin showing the continent-ocean transition (Jolivet et al., 2015a). The main observation on this profile is a 70-km wide zone of highly extended crust (the Gulf of Lion MCC), extracted from below low-angle detachments dipping toward the continent (Fig. 7). This domain is made of lower crustal material as suggested by seismic refraction data (Gailler et al., 2009) (see a discussion below). Further south, toward the oceanic domain, the Moho reaches the base of the sedimentary cover, and exhumed mantle is observed before the true oceanic crust. The exhumed lower crust is then cut by a series of normal faults dipping toward the ocean and delimiting half-graben filled with *syn*-rift sediments. An erosional surface (red line on the profile) observed at the top of the syn-rift deposit across the entire profile (Bache et al., 2010) shows that rifting was active while most of the future margin was above sea level, although the crust was already highly thinned, suggesting that the lithosphere was thin/hot and that the topography was potentially supported by asthenospheric upwelling. Whether there was some lithospheric mantle left beneath the rift zone is debatable but if any it was thin.

The nature of the material forming the toe of the margin deserves some more discussion. Interpreted as lower crustal material in Gailler et al. (2009), Jolivet et al. (2015a) or Granado et al. (2016), it could

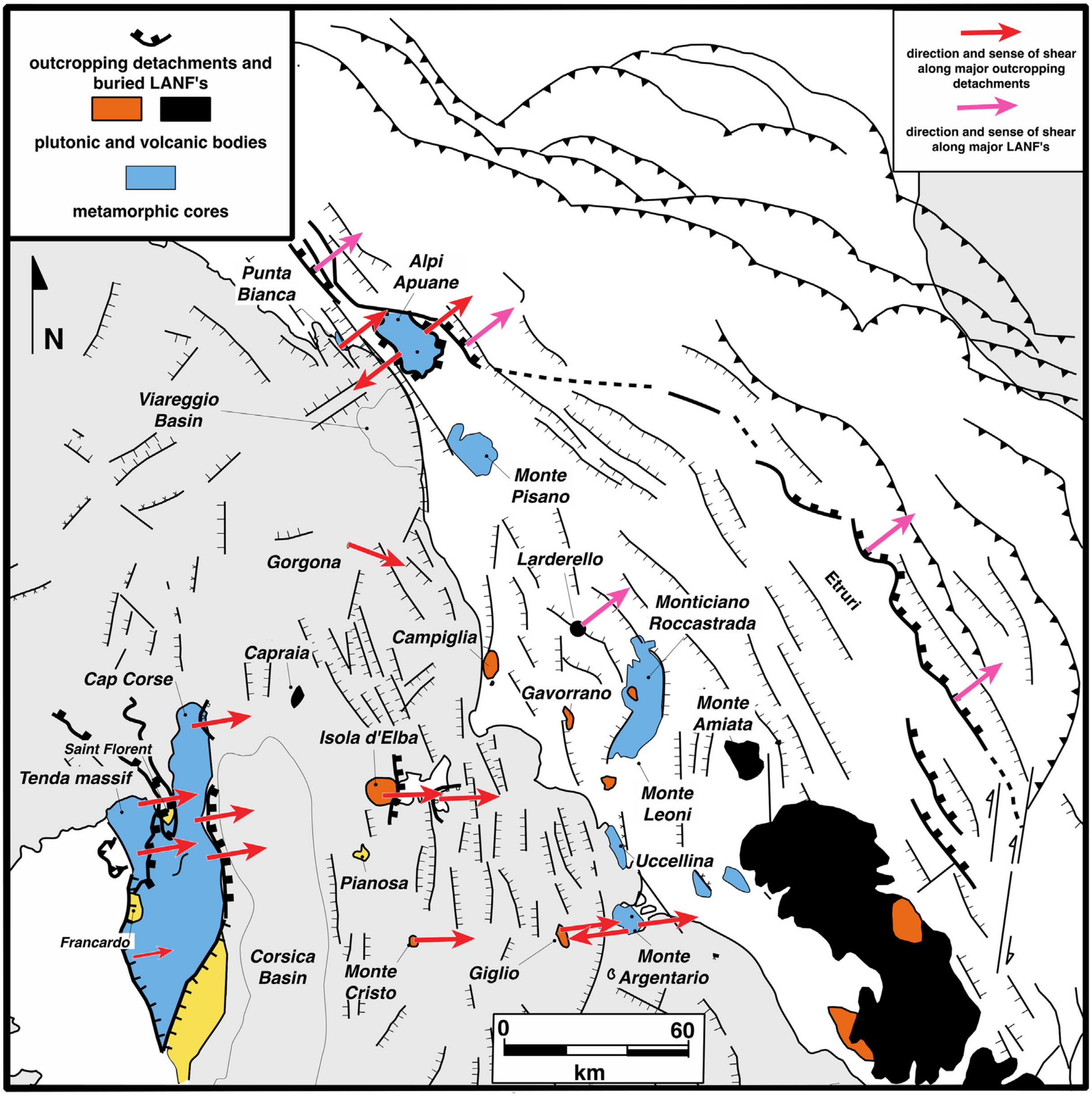

Fig. 6. Tectonic map of the Northern Tyrrhenian region and Northern Apennines, from Jolivet et al. (Jolivet et al., 1998).

also be serpentinized mantle. We however think that this is unlikely for the following reasons. This part of the margin was cut after its exhumation by a series of normal faults dipping toward the ocean and sediments were deposited within the then produced half-grabens, a situation that is nowhere observed with a serpentinite basement. Then, the observed unconformity at the top of this exhumed material suggests that the 70 km of outcrops were eroded in subaerial conditions before the deposition of the Aquitanian-Burdigalian marine sediments above. This would imply that 70 km of exhumed mantle were cropping out at the surface and eroded, an unlikely situation as well. On the other hand, exhumed lower crustal material forming a large core-complex is a more reasonable situation. The comparison with the Woodlark Basin (Abers et al., 2002; Taylor and Huchon, 2002) suggests that the Moho discontinuity was uplifted at the time of rifting in this hot environment, leading to the erosion of the exhumed material.

Overall, a complete cross-section running from the Gulf of Lion to Calabria and the Ionian subduction zone passing through Sardinia (Fig. 7b) also shows some asymmetry in the distribution of extension. Across the Liguro-Provençal Basin, the two conjugate margins appear different with a wider margin in the Gulf of Lion on the northwestern side compared to the southeastern side in Sardinia. The same difference can be noticed across the South Tyrrhenian Sea with a wider margin east of Sardinia than on the Calabrian side. This suggests that the mechanism leading to the formation of the Liguro-Provençal Basin and the Southern Tyrrhenian Sea had some component of asymmetry as well.

2.4. South Atlantic margins

Thanks to the power of seismic data acquisition for industrial purposes, new images of passive margins have recently become available, and especially in volcanic margins of the South Atlantic Ocean. Clerc et al. (2015a) have interpreted a seismic profile shot offshore Uruguay that display reflections down to the Moho with an unprecedented resolution (Fig. 8).

The studied domain lies at the southern limit of the Pelotas Basin (see also (Stica et al., 2014; Geoffroy et al., 2015). Rifting dates back to the Late Early Cretaceous and was coeval with the emplacement of the Parana-Etendeka Large Igneous Province (LIP) around 133–130 Ma

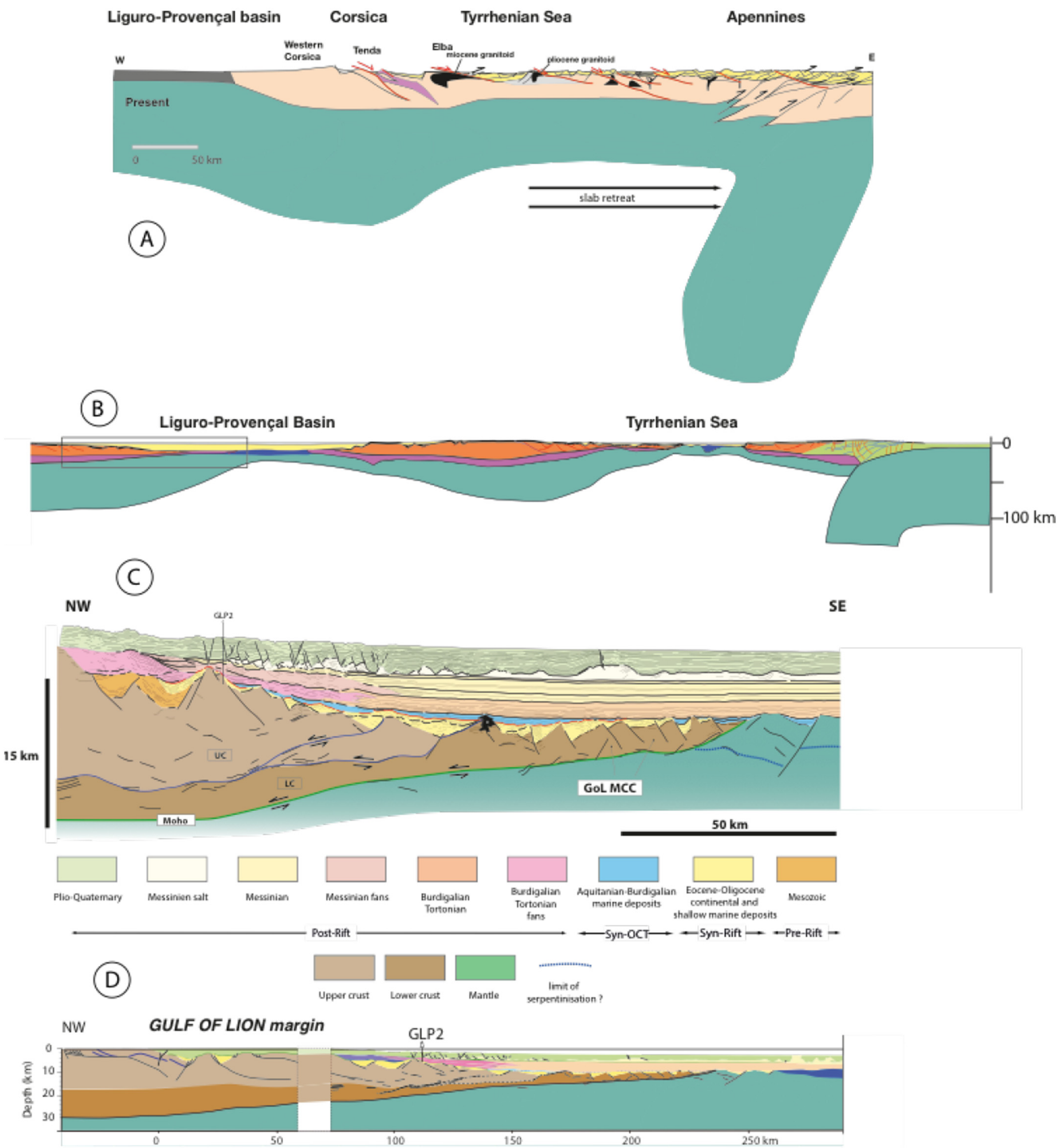

Fig. 7. Cross-sections of the Liguro-Provençal Basin and Tyrrhenian Sea (Jolivet et al., 1998; Jolivet et al., 2015a). A: section across the Northern Tyrrhenian and the Apennines. B: a complete section from the Provençal margin and Gulf of Lion, across the Liguro-Provençal Basin, Sardinia and the South Tyrrhenian Sea.

(Gladczenko et al., 1997; Franke, 2013). In this particular area, the margin shows 8 km thick wedges of seaward dipping reflectors (SDR) and this part of the margin is devoid of post-rift salt (Gladczenko et al., 1997). Below thick post-rift deposits, the margin shows a progressive thinning of the crust and a transition to typical oceanic crust over some 150 km. The formation of SDR wedges appears to be controlled by a series of continentward shallow-dipping normal faults (CDNF).

The Moho, clearly visible on the profile, is shown by prominent reflectors with a stepwise geometry. Two slightly steeper ramps are observed on either sides of a domain with flatter Moho and less intense reflections. Numerous more or less continuous reflectors above the Moho indicate ductile deformation of the lower crust. These reflectors display a sigmoidal shape. They are bent toward the strong Moho reflectors, a geometry that is reminiscent of ductile shear zones with a top-to-the west sense of shear. In between the two ramps, other shear zones can be seen but they are more symmetrical, suggesting a stronger

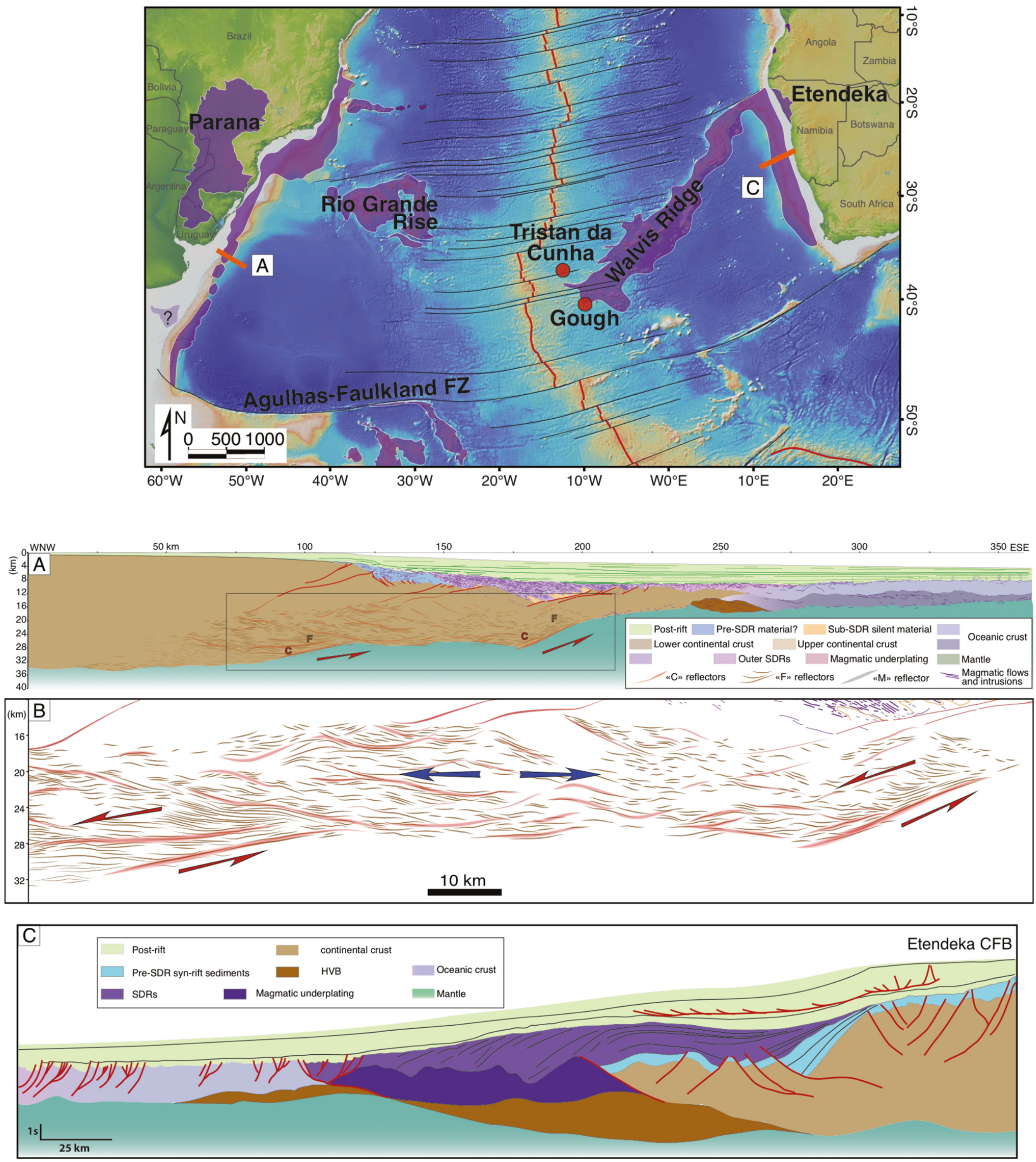

Fig. 8. Interpretation of industrial seismic profiles across the Uruguay margin (Clerc et al., 2015a) and the conjugate Namibia margin (Gladczenko et al., 1997). SDR: Seaward-dipping reflectors, HBV: High Velocity Body.

component of pure shear. The overall asymmetry of deformation in the lower crust indicates an extraction of the mantle from below the lower crust, toward the ocean. The shallow-dipping CNDF controlling the deposition of SDR's in the upper crust are compatible with the same shear sense and suggest an extraction of the lower crust relative to the upper crust toward the ocean. The whole crust and part of the lithospheric mantle thus show an asymmetric pattern of deformation and a component of shearing top-to-the continent. The strong seismic contrast shown by the Moho and other reflectors in the lower crust is possibly an indication of some magmatic underplating although it remains to be ascertained. It would nevertheless be in line with the presence of thick SDRs in the upper crust.

The geometry of the Uruguay margin is thus comparable with that of the Gulf of Lion margin with a top-to-the continent simple shear component distributed across the whole crust and part of the lithosphere. Like in the Gulf of Lion, rifting was also active in a high heat flow environment due to the presence of a plume below the rift, attested by the Paraña-Etendeka LIP, and the lithosphere was thus probably very thin at the time of rifting. Note however that in that case, there was neither lower crust nor mantle exhumed all the way to the surface because of the thick volcanic deposits at the time of rifting.

Published seismic lines on the conjugate margin of Namibia, in a similar environment associated with the emplacement of the Etendeka LIP suggest a similar geometry with CDNF and thick SDRs (McDermott et al., 2015) (Fig. 8). The asymmetry of deformation was thus opposite on either sides of the rift in the Early Cretaceous, thus showing a more symmetrical situation than in the Gulf of Lion at large scale. Becker et al. (2016) however suggest a significant asymmetry illustrated by the different dip of SDR's on either sides based on conjugate margins further south, which they interpret with a simple shear mechanism at the time of rifting, with a west-dipping detachment. Note that such a detachment would be compatible with the asymmetry seen on the Uruguay profile. The possibility is thus open of a significant component of asymmetry but probably not to the extent of what is observed in the Liguro-Provençal Basin and the Tyrrhenian Sea.

The relation shown in the South Atlantic passive margins between continentward-dipping normal faults and SDR wedges can be observed thanks to the deep penetration and high resolution of industrial seismic lines. Alternative interpretations have been proposed earlier to explain the ocean-ward tilt of SDRs. Some interpretations involve steep normal faults dipping toward the continent (break-up fault), localizing the ascent of magma and accommodating the formation of the wedge of SDRs (Quirk et al., 2014). In this case no low-angle ductile shear zone is involved in the lower crust. Another proposed mechanism uses the load imposed by the dense volcanic material on the elastic crust (Buck, 2017). The magma intrudes the crust as a vertical dyke and spreads laterally. Its weight flexes the crust on either side and forms the wedge of SDRs. Ridge jumps explain the successive generations of wedges observed on seismic profiles. No lower crustal shearing is involved in this type of mechanism. We prefer the former mechanism because it takes into account the geometries we see on the new seismic profiles we have studied. Moreover, continent-ward dipping normal faults and/or shear zones are not restricted to volcanic margins. They are also found on highly sedimented non-volcanic margins of the South Atlantic (Clerc et al., 2017) suggesting that SDR's are not the main cause of their formation.

2.5. The Afar region

The Afar region (fig. 9) is often considered a passive volcanic margin in the making (McKenzie et al., 1970; Le Pichon and Gaulier, 1988; Hammond et al., 2011). Located above a plume (Morgan, 1971; Marty et al., 1996; Hofmann et al., 1997; Ebinger and Sleep, 1998; Pik et al., 2006; Montagner et al., 2007) within the triple junction between Arabia, Somalia and Nubia, where the Gulf of Aden and the Red Sea ridges meet the East African Rift, it is characterized by active extension and volcanism since about 30 Ma (Hoffmann et al., 1997; Manighetti et al., 1997; Pik et al., 1999; Ebinger and Casey, 2001; Bellahsen et al., 2003; Pik et al., 2008; McClusky et al., 2010). After the emplacement of the Afar traps in the Oligocene, intense crustal thinning was recorded over a vast area east of the Ethiopian Plateau after 25 Ma (Wolfenden et al., 2004; Pasyanos et al., 2009; Hammond et al., 2011). The recent kinematics of extension has been described in details (McClusky et al., 2010; Kogan et al., 2012) but the evolution of rifting, from 25 Ma to the eruption of the massive Stratoid flood basalts some 4 Ma ago, remained largely unknown. Thanks to new geophysical investigations (Hammond et al., 2011) and a new field survey across the Central Afar magmatic segment, a new scenario is now available (Stab et al., 2016). The new cross-section (fig. 9) shows that extension has been distributed over a large domain with normal faults dipping mostly toward the Ethiopian Plateau and that the lower crust is largely injected with magmatic material.

The amount of extension suggested by the observed normal faults and their estimated offset is larger than shown by the actual crustal thickness shown by seismic investigations (Hammond et al., 2011). The crust in excess was thus attributed to massive underplating, which is consistent with the magmatic character of this Central Afar segment and its direct feeding by mantle plume derived melts (Pik et al., 2017). The exact geometry of the underplated material is actually difficult to constrain. The solution shown in Stab et al. (2016) is a consequence of the hypotheses made during section balancing, which involve some connection between the largest normal faults in the upper crust and some localized extensional shear zones in the lower crust. This localisation would induce a sort of asymmetrical boudinage of the lower crust and the distribution of the underplated material is then constrained by this geometry. No deep seismic data are available that could confirm or disprove this hypothesis. The most important observation for the topic of the present paper is however the attitude of normal faults along the entire section of this Central Afar segment (fig. 9). Except for the most recent normal faults related to the localization of rifting, all normal faults, whatever their offset, dip toward the continent, as do the large normal faults bounding the Ethiopian Plateau (Stab et al., 2016).

Another important observation is the difference between the Yemen margin and the Afar region. The Yemen margin is short compared to the width of the Afar region from the margin of the Ethiopian Plateau to the Red Sea where a progressive thinning is observed. One could however argue that active extension and magmatism are nowadays observed within the Afar triangle and not in the Red Sea along this transect (fig. 9). It is thus possible that the future oceanic domain forms in the Asal Rift and not in the Red Sea, which would make the margin to the NE much wider than the present-day Yemen margin. We cannot exclude this possibility, but the asymmetry of deformation remains for earlier extension during which most of crustal thinning was so far accommodated.

Although no more detailed information is available on the exact geometry of the continental Moho below the Afar and no detailed structures can be envisaged for the lower crust, this section offers some similarities with the Uruguay margin. The upper crust is affected by numerous normal faults that all dip toward the continent. The density of normal faults in this region suggests that strain is distributed and the lithosphere weak with predominant ductile deformation, which is confirmed by the pattern of deformation shown by GPS measurements (Kogan et al., 2012). The Ethiopian Rift further south shows a strongly localized deformation, while the transect studied here shows a progressive velocity gradient distributed over at least 300 km (Kogan et al., 2012). The same authors conclude that a combination of mechanical and thermal erosion of the continental lithospheric mantle leads to a widening of the deforming zone (wide rift in the sense of Buck (1991) northward, which is in line with the observation that seismicity is rare below 20 km underneath high magmatic segments of the rift (Yang and Chen, 2010), making the Afar region an example where the resistance of the continental lithosphere resides in the crust instead of the upper mantle (Maggi et al., 2000a, 2000b; Jackson, 2002). Geological observations of the distribution of normal faults and geodetic measurements thus suggest that the lithosphere is thin and weak below the Afar region, reinforcing the similarity with the Uruguay margin also developed above a mantle plume. This is in agreement with new geochemical and isotopic data which highlight that the subcontinental mantle beneath this magmatic segment was most probably removed very early, being replaced by channelling of the underlying mantle plume head (Pik et al., 2017). The asymmetry of deformation indicates a component of simple shear distributed across the whole thickness of the crust and remaining lithospheric mantle and the sense of shear suggests a northward displacement of the mantle relative to the crust.

It should be noted at this stage that this interpretation is based upon the new map produced recently by Stab et al. (2016), which puts the

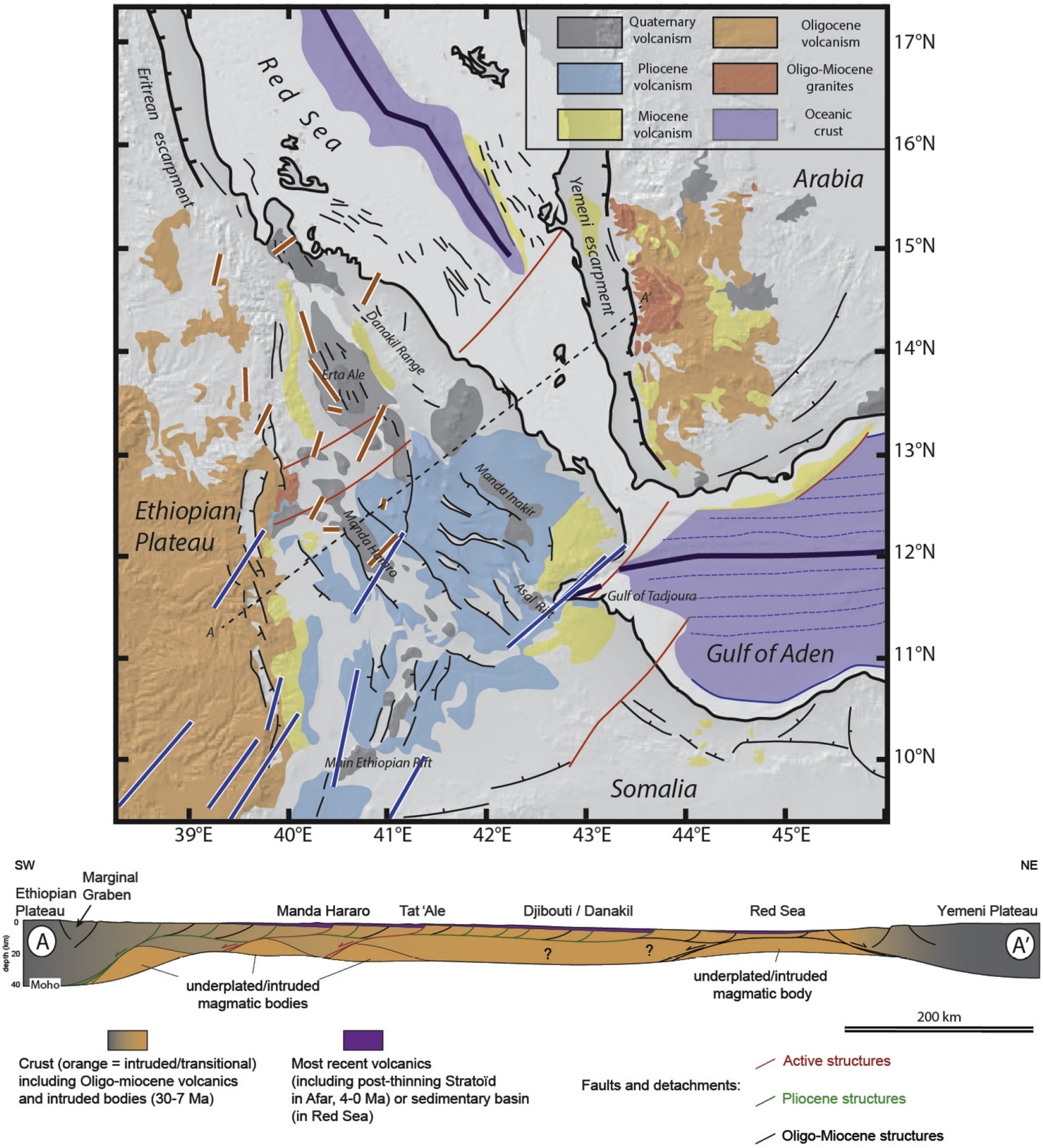

Fig. 9. tectonic map of the Afar region and a simplified cross-section through the Afar and Red Sea modified from Stab et al. (2016) and Pik et al. (2017).

emphasis on faulting to explain the consistent oceanward tilt of volcanic products in the study area. Earlier interpretations instead favoured extension accommodated, to a large extent, by magma intrusion and less by faults (Wolfenden et al., 2005; Bastow and Keir, 2011; Corti et al., 2015). This component of extension, without faults, is likely important and is emphasized also in the case of volcanic passive margins (Buck, 2017). However, in the case of the Afar, a large part of the extension is accommodated by faults as shown by Stab et al. (2016). We discuss in this paper the tectonic component of extension in region with high heat flow and thin lithosphere, while the interaction between magmatic extension and tectonic extension is another topic that should be studied as well. Bastow and Keir (2011) have suggested that the two extension mechanisms are both important but at different stages of the formation of a rift evolving into a margin.

3. Discussion

These various examples all show an asymmetrical deformation pattern over vast domains (several hundreds of kilometres), suggesting a component of simple shear through the entire crust at least. Faugère and Brun (1984) and Brun et al. (1985) (see also Brun (2002) for a more recent synthesis), based on analogue experiments with dry sand and silicone, have shown that domino-style faulting with a predominant tilt sense of normal faults in the brittle crust is correlated with a simple shear component in the ductile lower crust, normal faults being synthetic to the lower crust sense of shear. One can thus use the asymmetry of deformation in the upper crust to deduce the sense of simple shear at crustal-scale. The example of the Uruguay margin is an illustration of this relation as the continentward-dipping low-angle normal faults offsetting the SDRs are associated with ductile shear zones in the lower crust with the same sense of shear. The Gulf of Lion or Uruguay margins examples show that this simple shear component involves the entire crust and that even the Moho acts as a shear zone accommodating the extraction of sub-continental lithospheric mantle from below the margin.

The three examples taken from the back-arc basins of the Mediterranean realm show that a component of simple shear can be observed at the scale of the whole crust during extension in these environments with a high heat flow and thin lithosphere. One fundamental difference should however be pointed out. In the Aegean and the Gulf of Lion, low-angle normal faults and extensional shear zones dip away from the trench, while they dip toward the trench in the Northern Tyrrhenian Sea and the Apennines. This observation shows that the asymmetry of deformation at crustal scale cannot originate from the anisotropy of the crust inherited from the earlier compressional stages. If in the Aegean the detachment seems to reactivate earlier thrusts, in the case of the Tuscan Archipelago, Tuscany and the Apennines, the LANF have an opposite dip compared to earlier thrusts and the same can be said about the Gulf of Lion where the former Pyrenean and Provençal thrusts dip opposite to the detachments that have exhumed the lower crustal material seen nowadays at the toe of the margin (Gorini et al., 1993; Mauffret et al., 1995; Séranne et al., 1995; Séranne, 1999; Lacombe and Jolivet, 2005). Tectonic heritage could be, and probably is, an important localizing factor in some regional examples, but of second order when the lithosphere is hot and the crust weak.

All studied regions have in common a high heat flow and a thin lithosphere, either in the upper plate of subduction zones or above mantle plumes. In such contexts, one may expect a weak lower crust and absence or quasi-absence of lithospheric mantle, favouring a possible viscous coupling between the lower crust and the flowing asthenosphere. All these situations where the heat flow is high, either above a mantle plume or in a back-arc domain, thus offer the possibility that the lithosphere is sheared by a differential motion between asthenosphere and crust, but this differential motion could have different origins. There is no possible direct measurements of the velocity of asthenospheric flow, but the example of the migration of volcanism from East Africa to Arabia and East Anatolia during the Oligo-Miocene suggest velocities around 10 cm/yr (Faccenna et al., 2013b), which should be compared with the 2–3 cm/yr of crustal deformation in the Aegean or the Afar, for instance. Much higher velocities in crustal displacements are however recorded in some examples such as the opening of the Southern Tyrrhenian Sea (up to 19 cm/yr) (Nicolosi et al., 2012).

Different conceptual models can then be discussed. The cases of the Gulf of Lion and Uruguay passive margins are very similar in terms of finite structures and kinematics at crustal scale, but the overall contexts are entirely different, a back-arc basin versus a rift giving birth to a large ocean. The cases of the Gulf of Lion and Aegean region can be explained by a differential motion between the crust and the mantle driven by slab retreat, the mantle flowing faster than the crust (fig. 10, fig. 11). In the case of the Afar, the plume material moves faster than the African plate after its collision with Eurasia (Faccenna et al., 2013b). In both cases, a differential motion between the mantle and the crust is a possible cause for the simple shear component, although the origin of this differential motion is different.

3.1. Back-arc region, asthenospheric flow and slab retreat

In back-arc regions, the asthenosphere flows toward the trench, following the retreat of the slab. This induced in the Aegean region and Gulf of Lion an asymmetric strain pattern in the crust and the extraction of lower crust and mantle below low-angle shear zones and faults dipping toward the overriding plate. The asymmetry of the distribution of finite extension along the Provençal margin-to-Calabria transect also suggests a strong coupling with mantle flowing southeastward (Jolivet et al., 2015a).

Such a crust-mantle coupling can also be found in the parallelism between crustal stretching directions and mantle stretching inferred from seismic anisotropy. We have observed (Jolivet et al., 2009) a systematic parallelism between the direction of stretching in metamorphic core complexes of the three main Mediterranean back-arc regions and the fast direction of SKS-wave splitting. These back-arc regions are those with the thinnest lithosphere and the hottest one in the Mediterranean realm. They accommodated large extension and large slab retreat, amounting to several hundreds of km. We thus relate stretching in the mantle and in the crust to the same tectonic event. The numerical model we present below strengthens this interpretation by showing that the mantle is indeed sheared below the Moho when the slab retreats and that the observed shear sense is compatible with the asymmetry of deformation seen in the Aegean region.

The question of the main sense of shear observed in the crust of back-arc regions toward the overriding plate (Cyclades, Gulf of Lion) or toward the trench (Rhodope, Northern Tyrrhenian Sea, Alboran Sea after 20 Ma) should now be discussed. Jolivet et al. (2008) have discussed this difference and found that top-to-the trench shearing is associated with subduction with little or no convergence. This is clearly the case during rifting of the Northern Tyrrhenian Sea and extension of the internal zones of the Apennines in Tuscany. The direction of relative motion between Adria and Eurasia is almost parallel to the Apennines at this latitude and subduction is not associated with overall convergence perpendicular to the trench. Subduction results only from slab sinking and retreat.

Indeed, subduction does not require convergence to occur if the dense slab subducts only under its own weight. In this case the amount of subduction exactly equals the amount of retreat (Faccenna et al., 2003; Jolivet et al., 2008). The velocity of trench retreat thus equals exactly the velocity of subduction across the Northern Apennines, while subduction is the sum of slab retreat and convergence across the Hellenic Trench or the Calabria Trench. Fig. 11 (inset) shows these different situations and the inferred mantle flow below. With convergence and no slab retreat, asthenospheric flow is purely the consequence of convergence and a differential motion then exists between the overriding crust and the mantle, the latter flowing at the same velocity as convergence and thus faster than the crust. With slab retreat and no convergence, the velocity of subduction equals that of slab retreat and mantle and crust move at the same speed, without any differential motion. The Northern Tyrrhenian Sea, or the Alboran Sea after 20 Ma, enters in this second category (fig. 11b). The Aegean Sea or the Gulf of Lion-Calabria transect involve both convergence and slab retreat (fig. 11a) and the mantle flows faster than the crust, thus creating a component of shearing at the base of the crust.

The case of the Aegean back-arc domain is well illustrated by a numerical model shown in fig. 12. For details on the modelling procedure and initial setup, the reader is referred to Menant et al. (2016b). The initial rheology of the overriding plate is made of a single crustal layer (wet quartz) above the lithospheric mantle. The initial purpose of this model was to study the effect of slab tearing and arc magmatism on the deformation of the overriding plate, which are not discussed here (see Menant et al., 2016b). Slab tearing occurs because the subducting material changes along the strike of the subduction zone, continental versus oceanic lithosphere (fig. 12a). Fast slab retreat is then observed where it is still attached and back-arc extension proceeds in the upper plate. Figs. 12b and 12c show two vertical sections of the velocity field from the back-arc region to the trench at 14 and 21 Myrs, decorated with the different phases (upper panel) and viscosity (lower panel). Viscosity and velocity changes with depth are also shown along a 1-D vertical profile (see inset of fig. 12). The horizontal velocity of the flow during retreat reaches a maximum at a depth of about 90 km in the asthenosphere. It decreases upward toward the overriding plate and downward toward the down-going plate. A gradient of velocity is observed in the ductile (i.e. low viscosity) lower crust, the lower part flowing faster than the upper crust, thus inducing top-to-the north

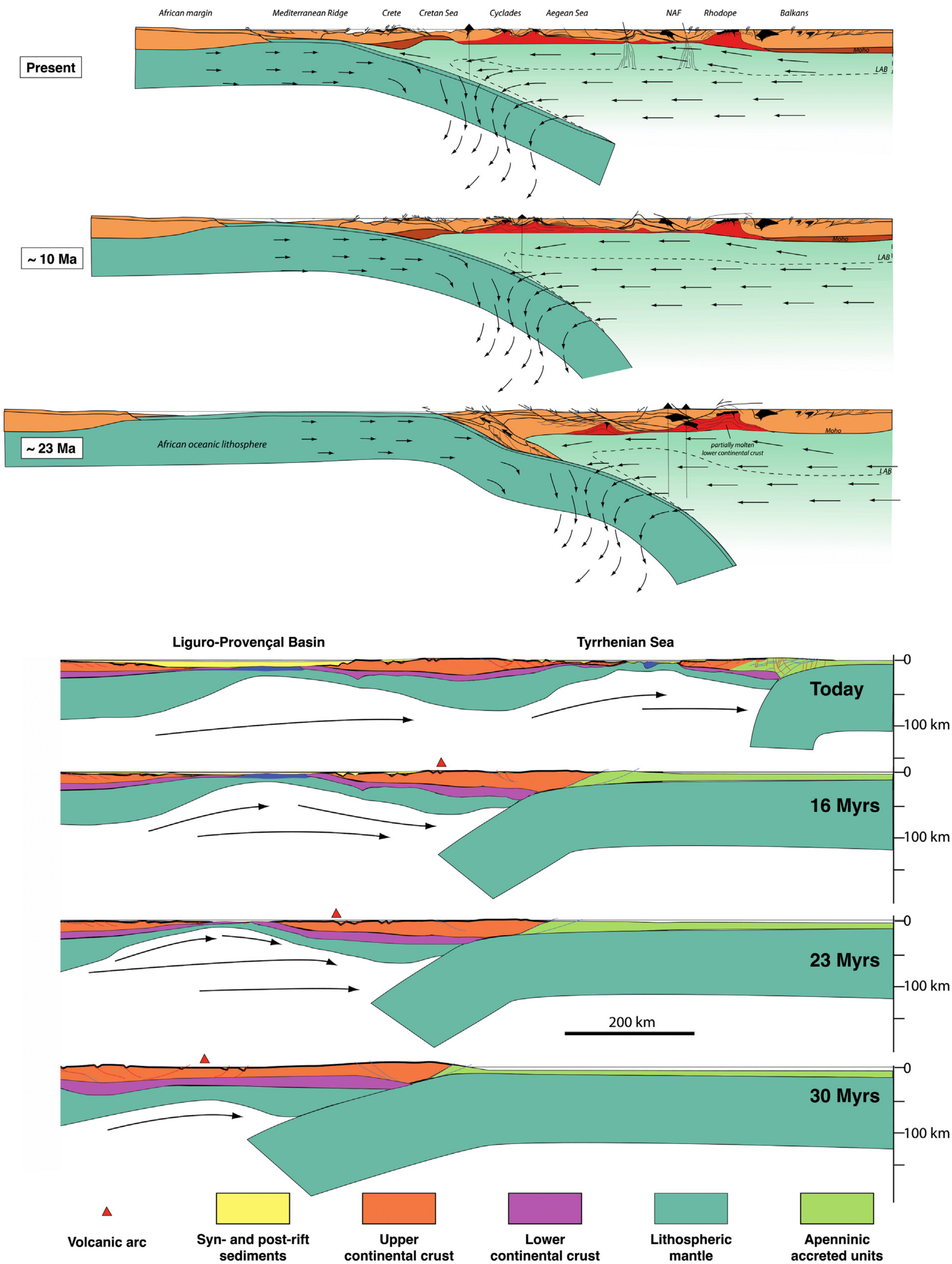

Fig. 10. Reconstructions of the evolution of the Aegean Sea (upper) and the Provence-Calabria transect (lower).

shearing similar to what is observed in the Cyclades. This example shows that the asthenospheric flow is able to cause an asymmetric shearing of the crust when the heat flow is high and the lower crust weak, as suggested by the natural examples summarized above, confirming the conclusions of Sternai et al. (2014), also supported by recent analogue models (Chen et al., 2016). The latter paper approaches this question with analogue models and the authors indeed conclude that back-arc extension in narrow retreating subduction zones is due to a gradient of basal drag force below the overriding plate. Although with a different approach, Pauselli and Ranalli (2017)

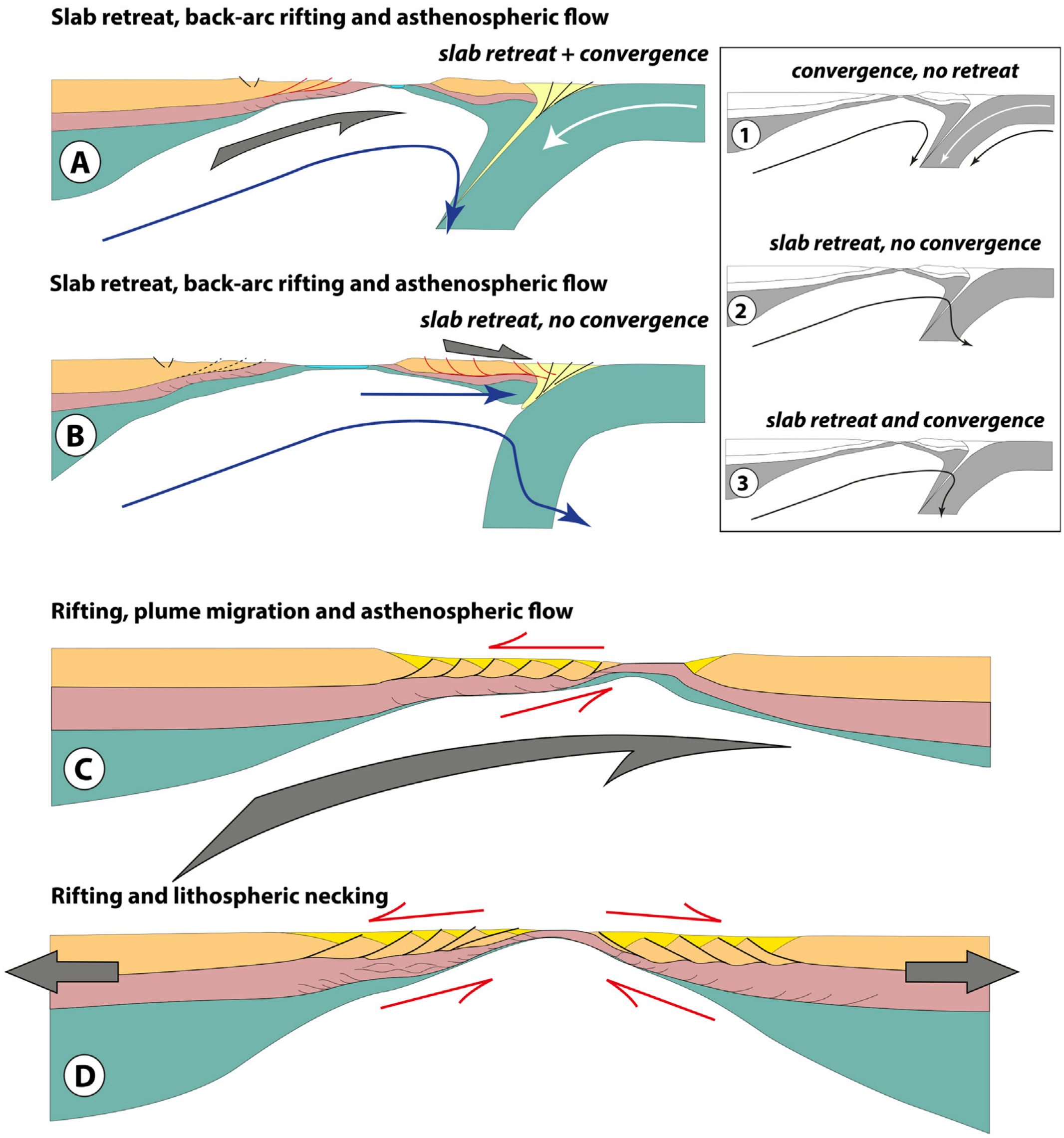

Fig. 11. Interpretation of the relations between slab retreat, mantle flow and crustal deformation in different back-arc/rift settings. A and B: Mediterranean back-arc basins. A: Aegean Sea and Gulf of Lion-Southern Tyrrhenian Sea, slab retreat is associated with convergence, asthenospheric flow below the overriding plate thus goes faster than retreat and extension inducing a shearing of the lithosphere top-to-the upper plate B: northern Tyrrhenian Sea, subduction is only caused by slab sinking without any convergence; asthenospheric mantle thus flows at the same velocity as slab retreats. C: Afar and Red Sea; the rift develops above fast northward moving mantle inducing shearing in the lower crust that is transmitted to the whole lithosphere. This situation induces the formation of normal faults dipping toward the continent and an asymmetric width of margins. D: South Atlantic rift hot margins; extensional stresses are due to far-field forces imposed on the upper part of the lithosphere and a component of shearing develops along the base of the lithosphere in the necking zone. Inset: expected asthenospheric flow below the overriding plate of subduction zone with convergence only (1), slab retreat only (2) and a combination of the two (3).

recently reached partly similar conclusions through the study of rheological profiles across the Apennines and argue that the active low-angle Alto Tiberina normal fault is localized at a point where the total strength of the brittle layer and the whole lithosphere reaches a maximum. They further concluded that the low dip of the Alto Tiberina Fault is due to a basal shear related to lithospheric delamination (thus associated with eastward migration of extension) during slab retreat or to low friction coefficient and high pore pressures.

Other differences can be noted. A comparison between the Cyclades and the Northern Tyrrhenian Sea seems to indicate a warmer regime in the Cyclades. This is shown by the occurrence of migmatite-cored MCCs in the Cyclades, absent from Corsica to the Apennines. This is true also further east in the northern Menderes Massif where Oligo-Miocene migmatites are observed below the Simav Detachment (Bozkurt et al., 2011; Cenki-Tok et al., 2015), a probable eastern extension of the NCDS (Jolivet et al., 2010b). This is also suggested by the fact that the Tyrrhenian Sea shows a clearer west to east propagation of extension, with diachronous *syn*-extension intrusions and syn-rift basins. Extension was thus not active during a long period at the same place and it followed the retreat of the slab, with present-day seismogenic extension along shallow east-dipping normal faults in the Apennines. The warmer regime of the Aegean, leading to a weaker crust, can be attributed to a probable thicker orogenic crust and a longer delay between crustal thickening and extension. In the Northern Tyrrhenian Sea and the Apennines, extension sets up immediately behind the thrust front and affects a crust that had not enough time to thermally equilibrate. Moreover, although slab retreat has accelerated some 35–30 Ma in the Aegean, extension had started earlier as soon as the Eocene to form the Rhodope MCC.

Using a comparison with the numerical model of Menant et al. (2016b) (fig. 12) one may propose the following evolution (Fig. 4). In the first stages of slab retreat (see the stage at 14.5 Myrs in the model),

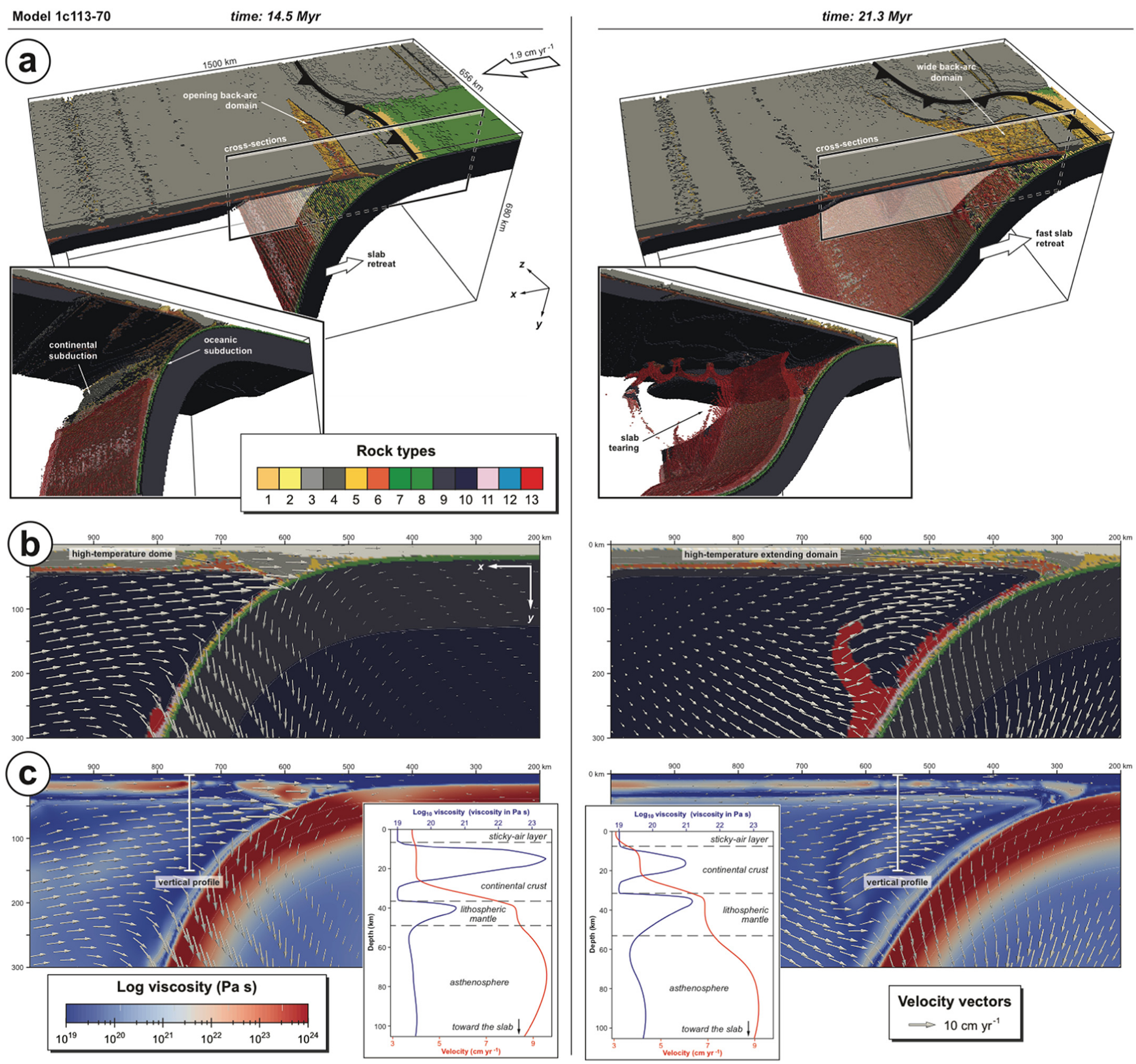

Fig. 12. a numerical model of slab retreat in 3D (for initial setup and more details, see (Menant et al., 2016b). A: 3D views of two stages of evolution of the model at 14.5 and 21.3 Myrs. The upper plate lithosphere is made of a one-layer continental crust (also for the small continent within the lower plate) leading to a two-layer rheological stratification for the continental lithosphere (with lithospheric mantle). The base of the lithosphere is set at a depth of 113 km (1300 °C isotherm, ~13 °C/km). The oceanic crust has a 70-Myr thermal age. Lower plate velocity (material inflow across right boundary) is set to ~1.9 cm yr-1. Material flows outward across upper and lower boundaries to ensure mass conservation. Free slip conditions are set at both front and back boundaries. Colours represent the different rock types: 1 – sediments; 2 – partially molten sediments; 3/4 – dry upper/lower continental crust; 5/6 – hydrated/partially molten continental crust; 7 – dry oceanic crust; 8/9 – hydrated/partially molten oceanic crust; 10 – dry lithospheric mantle; 11 – dry asthenosphere; 12/13 – hydrated/serpentinized mantle; 14 – partially molten mantle. Asthenosphere and other phases are cut off for clarity. B and C: vertical sections through the model at 14.5 and 21.3 Myrs showing the velocity field. B is decorated with rock types and C with viscosity. Inset: 1-D vertical profiles of viscosity and velocities at 14.5 and 21.3 Myrs.

one single large HT dome forms in the overriding plate. It is bounded trenchward by a trenchward-dipping interface and the velocity toward the trench increases through the dome and through the interface between the dome and the crust further south, implying a normal motion along this interface, thus with a sense of shear toward the trench within a shear zone restricted to the crust. This situation of a large MCC exhumed below a south-dipping detachment is similar to the case of the Rhodope in the Eocene. In a second stage (see the stage at 21.3 Myrs in the model) the HT extending domain is wider and thus more sensitive to the basal shear imposed by the faster motion of the mantle toward the trench and the gradient of top-to-the north shear observed across the lower crust will control the deformation of the entire crust, a situation that is similar to the Cyclades in the Oligocene and Miocene. The inversion of shear sense observed from the Rhodope to the Cyclades could thus be inherent to the process of slab retreat and associated post-orogenic extension of a thickened and hot crust. The case of the Northern Tyrrhenian Sea could be interpreted in the same line with a colder regime because extension sets at short distance from the trench within the accretionary wedge, thus in the situation of the first stage observed in the model, with a detachment dipping toward the trench.

The combination of the absence of convergence and the colder regime could then explain the observed evolution with normal faults dipping toward the trench.

The polarity of the asymmetry of normal faults and sense of ductile shear in the upper plate of the Mediterranean back-arc basins thus seems controlled by the relative motion of the asthenospheric mantle with respect to the crust of the overriding plate and this in turn depends upon subduction dynamics, slab retreat, with or without convergence. We have so far considered that mantle flow is entirely driven by slab retreat and/or convergence but one should also consider the component of mantle flow related to the larger-scale convection. One can in a first approach exclude this problem in the case of the Western Mediterranean Sea because rates of slab retreat were fast there and are unlikely to be significantly modified by large-scale convection. On the opposite, Faccenna et al. (2013b) have proposed that the westward motion of Anatolia is part of a large toroidal cell involving mantle upwelling in the east, below the Afar, and down-welling in the Hellenic subduction zone. In this case the toroidal component of flow related to whole-mantle convection cell would add up to the toroidal flow related to slab retreat.

3.2. Rifting and crust-mantle coupling

The interpretation of recently acquired industrial seismic profiles across a number of rifted volcanic margins shows that continent-ward dipping normal faults are not observed only in volcanic margins (Clerc et al., 2016). Several profiles across the non-volcanic margins of the African continent on the Gabon and Angola margins show the same situation (Clerc et al., 2017). These magma-poor margins however also show intense ductile deformation and boudinage of the lower crust, suggesting high-temperature deformation, a very different situation from more classical magma-poor margins where normal faults dip toward the ocean and cut the whole crust (Whitmarsh et al., 2001; Manatschal, 2004; Reston et al., 2007; Ranero and Pérez-Gussinyé, 2010; Sutra et al., 2013). The Atlantic margins of Gabon and Angola and the margins of the South China Sea thus show a more ductile behaviour and were thus hotter at the time of rifting than classical magma-poor margins, despite the absence of significant volcanism and thus out of the magmatic influence of a mantle plume.

3.2.1. Cold versus hot margins

In agreement with observations along fossil passive margins exhumed in the Alps and Pyrenees, one may discuss a distinction between cold (Alpine/Galicia type) (Manatschal, 2004; Sutra et al., 2013) and hot (Pyrenean/Uruguay type) (Clerc et al., 2015b, 2016, 2017). The main difference between margins with continentward-dipping and oceanward-dipping normal faults thus seems the thermal state of the lithosphere at the time of rifting (hot vs cold margins) (Clerc and Lagabrielle, 2014; Clerc et al., 2016). Cold margins develop series of tilted blocks and the rift is often asymmetric with a predominant tilt sense. This asymmetry is often interpreted as a consequence of the localisation of one or several synthetic detachments that affect the whole lithosphere or at least the upper crust, the tilt sense being imposed by the sense of motion along the main detachment (Whitmarsh et al., 2001; Manatschal, 2004; Sutra et al., 2013). This type of model followed the discovery of low-angle normal faults in the Basin and Range Province, a situation soon applied to rifted margins (Wernicke, 1981, 1985). The often-used notions of "upper plate margins" and "lower plate margin" refer to the existence of detachments at the scale of the lithosphere (Lister et al., 1986, 1991). Alternative scenarios involving flexural rotation and the rolling-hinge model were then proposed that avoid the use of active low-angle normal faults (Buck, 1988; Wernicke and Axen, 1988; Lavier et al., 1999). More recently, strain localization along shallow-dipping normal faults and/or the asymmetry of tilted blocks is explained either by detachment along pre-existing shallow-dipping discontinuities (Le Pourhiet et al., 2004) or along a detachment (S-reflector) localized in the serpentinized mantle (Reston et al., 2007) or, instead, with a migration of the rift through time without the need of a large-scale detachment (Ranero and Pérez-Gussinyé, 2010; Brune et al., 2014). The last type of model also provides an explanation for the contrasting width of some conjugate margins. Cold margins are thus prone to an efficient localisation of deformation, either along large-scale detachments formed at different stages of rifting or within migrating rifts, both situations providing explanation for the observed asymmetry.

Rifting dynamics leading to the development of hot margins observed in many places does not fit any of the mechanisms summarized above. The dip of normal faults is toward the continent, deformation appears more ductile than in cold margins and a single large-scale detachment cannot explain the opposite dip of normal faults on the two conjugate margins. The notions of upper/lower plates do not apply. It is thus necessary to work on different dynamic processes.

3.2.2. Hot margins and shearing between crust and mantle

A comparison between hot volcanic margins and the rifting process at work nowadays in the Afar region can bring interesting insights. The asymmetry observed in the Afar region can be explained by an asthenospheric mantle flowing faster than the crust (fig. 11c). Faccenna et al. (2013b) indeed proposed that the hot mantle material in the region impacted by the Afar plume is channelized northward below the Red Sea and Levant region and reaches the Bitlis collision zone. This observation fits the migration of volcanism from 45 Ma to ~10 Ma from the East African Rift region south of Ethiopia to eastern Turkey (Ershov and Nikishin, 2004). The mantle signature of magmas in East Anatolia has increased since the Miocene, from an enriched mantle signature compatible with subduction toward intra-plate type magmas. At variance with this geochemical model, Pik et al. (2017), based on a detailed isotopic study, show a more complex evolution in space and time where different contributions are recognized in the source of magmas. The mantle plume signature is clearly recognized but it is locally mixed with a contribution of the thinned continental lithosphere and an evolution toward MORB shows up along the Gulf of Aden ridge. It remains that volcanism has migrated from south to north, all the way to Eastern Turkey. It is not everywhere the same molten material but one can reasonably assume that the origin of heat (the plume) is the same. Faccenna et al. (2013b) thus proposed a model in which the plume impacted the African lithosphere south of the Afar region and migrated northward and southward when the plume head was spreading under the lithosphere. At 30 Ma, when the African continental lithosphere collided with Eurasia, Africa slowed down dramatically and the plume gave rise to the Afar traps (Burke, 1996). In the meantime, the Gulf of Aden started to rift as a consequence of asymmetric boundary conditions in the north (Jolivet and Faccenna, 2000; Bellahsen et al., 2003). While the African plate was moving slowly northward, the plume material was still moving at a faster pace and travelled from the Afar region to Eastern Turkey between 30 and 10 Ma, carrying the newly formed Arabian plate (Bellahsen et al., 2003). The supposed mantle flow is northward relative to Africa and Arabia, in agreement with the pattern of SKS-waves anisotropy (Bagley and Nyblade, 2013) fitting the observed asymmetry of deformation in the Afar domain and the wider southern margin.

The Uruguay margin clearly shows an asymmetry at crustal scale from the Moho to the upper crust with an extraction of the lower crust and mantle from below the margin that is, in a first approach, reminiscent of the recent Afar situation or the Gulf of Lion in the Oligocene and Early Miocene. At variance with these examples, the conjugate Namibian margin also shows an asymmetry with some similar features and normal faults dipping toward the continent, but the sense of shear is thus opposite. At the scale of the South Atlantic rift the pattern then seems more symmetrical than in the Afar but a component of asymmetry can be envisaged with a predominant top-west sense of shear. As described above, a closer look at the margins structure shows some differences suggesting that the rifting was not exactly symmetrical. Let us consider in a first approach that it was symmetrical (fig. 11d).

During rifting, the upper crust was thus moving outward (toward Africa on the eastern side and toward South America on the opposite side) relative to the lower crust and mantle that were extracted in between. Such a situation tends to suggest that the asymmetry seen at the scale of one margin is not due to a large-scale flow of the plume mantle relative to the lithosphere, except if this flow was divergent with a centre exactly below the rift, which is unlikely. One then faces an alternative to conceive a model: either (i) the observed shearing of entire crust simply results from the necking of the whole lithosphere and the uplift of the mantle that is exhumed in the space open between the two pieces of lithosphere, thus creating a simple shear component along the mantle-crust interface, like along the rims of boudins (fig. 11d) or (ii) the crust moves outward from the centre of the rift faster than the underlying mantle because a traction is imposed on the upper part of the lithosphere mainly (fig. 11d). In the latter case (i), the main question is then the cause of this faster motion of the crust relative to the mantle or, in other words, what is the force that is moving Africa eastward and South America westward. In the case of Africa, three types of forces can be proposed: (1) at the time of South Atlantic rifting, Africa was moving toward the Tethyan subduction zone and the main force was the pull of the Tethyan slab sinking below Eurasia; (2) the mantle was flowing away from the plume and pushed on the topographic irregularities of the base of the African lithosphere; (3) higher heat flow above the plume made the lithosphere lighter and induced a large-scale doming, which favoured a gravitational sliding of the crust away from the centre of the plume. The three types of forces can also combine. In situations 1 and 2, far-field forces are imposed on the continental lithosphere and thus, in the rift region, where the heat flow is high, the only resistant layer able to transmit extensional stresses is the upper lithosphere, mainly the crust. Traction in the rift zone is thus imposed principally on the crust that moves faster outward than the mantle. This scenario could apply for hot margins, whether magma-rich or magma-poor.

Let us now consider that the Uruguay and Namibia margins are not fully symmetrical, with a component of simple shear during rifting (Becker et al., 2016). A comparison with the Afar or the Liguro-Provençal Basin / Tyrrhenian Sea transect would suggest a component of mantle flow toward the east that would stretch the Uruguay margin more than the Namibia margin, at the time of intracontinental rifting. This asymmetrical component might be seen also in the asymmetry of seafloor spreading (Müller et al., 1998, 2008). Müller et al. (1998, 2008) indeed note that, in average, spreading is above 3.5% faster on the South American side than on the African side. However, this asymmetry is not equivalent on all spreading corridors and it does not seem to be true at the latitude of Uruguay. The answer to this question depends much upon the exact position of the rift with respect to the Paraña-Etendeka plume at the time of rifting and on the mantle flow pattern around the plume at the same period. We thus leave this question open.

3.3. Extension and crust-mantle coupling

All these natural examples show that the continental crust and the lithospheric mantle can be deformed asymmetrically with a component of simple shear distributed across the whole thickness of the lithosphere when the lithosphere deforms in a high-temperature regime. The reasons behind this simple shear component are two-fold: (i) large scale necking of the lithosphere and formation of a shear zone when the mantle is uplifted in the necking zone (hot passive margins with formation of continentward-dipping normal faults and ductile deformation of the lower crust), (ii) relative motion of the asthenospheric mantle with respect to the lithosphere, either in back-arc domains (Aegean region) as a result of slab retreat or above plumes (Afar region). Numerical models have shown that, when the lithosphere is weak, a gradient of velocity can form within the lower crust (fig. 12). In this case one can speak of basal drag or basal shear, the crust being entrained by the mantle flow through viscous coupling. This is shown also by analogue modelling of narrow retreating slabs, where the forces driving extension in the back-arc domain are due to mantle flowing underneath toward the slab (Chen et al., 2016). In the case of a larger piece of continent, like when Arabia separated from Africa in the Oligocene, a similar basal drag force can be envisaged if the surface is large enough but an additional mechanism can be envisaged. One solution alternative to basal drag is that the flow of asthenosphere pushes on irregularities of the base of the lithosphere, a mechanism that was proposed by Stoddard and Abbott (1996) or Ghosh et al. (2013) and more recently on the basis of 3D numerical models of plume lithosphere interaction by Koptev et al. (2015) on the example of the East African Rift system.

Domains with constant fault dip sense over vast regions have been reported from other regions where a connexion with asthenospheric flow is not obvious. Two examples can be discussed here. The first example is the Gulf of Suez where the rift is divided in four tilt-domains where the dip of normal faults is constant through the entire rift, with dip inversion across transfer structures (Colletta et al., 1987; Moretti and Colletta, 1987; Bosworth and McClay, 2001; Bosworth et al., 2005). In this case rifting takes place far from the Afar plume and is not related to a back-arc environment. The Suez Rift corresponds to a failed attempt of propagation of the Red Sea toward the north. Also in contrast with the examples studied in the present paper, there is no evidence of deep crust exhumation and the main normal faults were formed with a steep dip. This sort of context is closer to a classical intra-continental rift that would have developed as a cold-type passive margin, had extension proceeded longer. The reason for the constant dip of normal faults is unclear in this case, but several models involving crustal-scale detachments or sequential faulting can be envisaged (Manatschal, 2004; Ranero and Pérez-Gussinyé, 2010).

A second example is the Basin and Range Province in the Western United States (Fig. 13). The dip and sense of normal faults show a clear regionalization with several large dip-domains, faults dipping either to the west or to the east (Stewart, 1980). This case is closer to the examples we have studied here as extension was distributed over a wide area (up to 800 km in *E*-W direction) and high-temperature metamorphic core complexes have been exhumed below low-angle detachments (Davis and Coney, 1979; Crittenden et al., 1980; Davis and Lister, 1988; Wernicke, 1992). As in the Aegean back-arc region for instance, this extension was achieved within a weak and hot lithosphere in a post-orogenic context, but far from a subduction zone. It was on this very example that the model of lithospheric-scale uniform-sense normal simple shear of the lithosphere was first proposed (Wernicke, 1981, 1985). So far, no clear model explains the distribution of shear sense across the whole Basin and Range and these dip-domains. Fig. 13 shows these dip domains and their relation to the long wavelength topography. The map shows a partial relation between topographic slope and fault dip. This may suggest a component of gravitational sliding as a control of fault dip. But it shows a relation between dip direction and the present-day topography. In order to understand this relation, a detailed study of the evolution of topography through time such as that recently published by Bahadori et al. (2018) and the development of normal faults would be required. Ricard and Froidevaux (1986) suggested that the long wavelength topography could be controlled by lithospheric thickness variations and they invoked lithospheric boudinage. Larger-scale processes may thus be at play. In any case the mechanisms explaining the distribution and asymmetry of extension in this case seem different from those we propose for the examples we have studied.

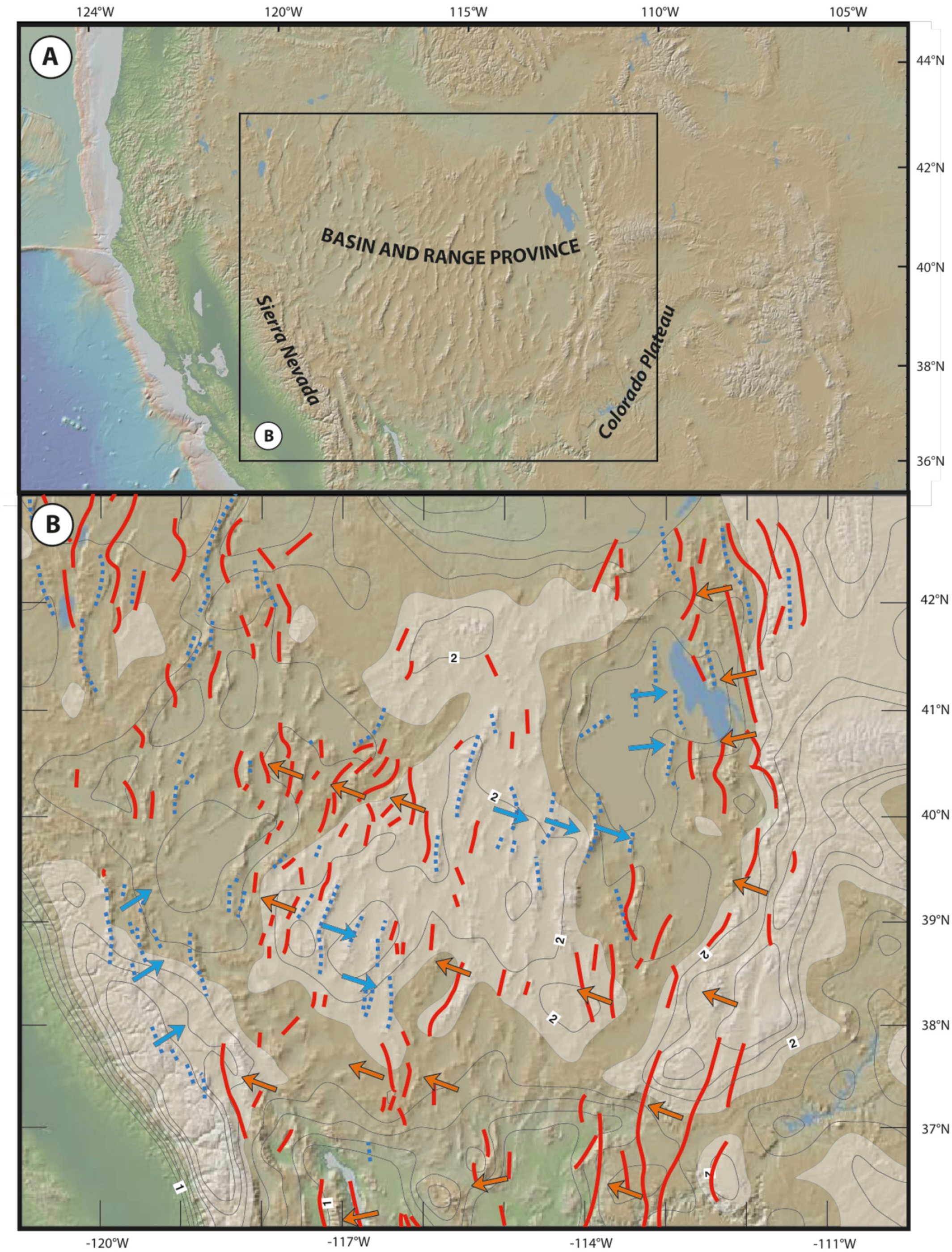

Fig. 13. Topography and dip-domains of normal faults in the Basin and Range Province (Western US). Red faults dip westward and blue ones dip eastward. Thin lines are contours of the filtered topography (contour interval 200 m). Arrows represent the sense of shear in the deep crust as indicated by the asymmetry of normal faults. Lighter-colored domains are above 1800 m. Fault dips domains after Stewart (1980). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4. Conclusion

The analysis of several crustal-scale extensional structures, the Gulf of Lion passive margin, the Uruguay volcanic passive margin, the Aegean Sea, the Northern Tyrrhenian Sea and the Afar, reveals that the whole crust has been extended with a component of simple shear parallel to the Moho. While simple shear is accommodated by a series of large-scale low-angle normal faults in the upper crust, it is more distributed in the lower crust down to the Moho, which can become a preferential shear zone. The chosen examples all have in common a distributed extensional deformation and a high heat flow, thus a weak crust and thin lithosphere. As the surface of the Earth is stress-free, the component of simple shear must be transmitted from below and implies a displacement of the crust relative to the mantle. Two main mechanisms can be proposed to explain this simple shear component: (i) large scale necking of the lithosphere and shearing parallel to the Moho in the necking zone (hot passive margins with formation of continentward-dipping normal faults), (ii) flow of the asthenospheric mantle underneath the lithosphere, in back-arc domains as a result of slab retreat (Aegean region or Gulf of Lion) or above plumes (Afar region). The presence of shallow-dipping heterogeneities in the crust inherited from earlier tectonic events can also reinforce the asymmetry of finite deformation but it is a second-order factor.

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