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Transfer zones in Mediterranean back-arc regions and tear faults

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Abstract – Slab tearing induces localized deformations in the overriding plates of subduction zones and transfer zones accommodating differential retreat in back-arc regions. Because the space available for retreating slabs is limited in the Mediterranean realm, slab tearing during retreat has been a major ingredient of the evolution of this region since the end of the Eocene. The association of detailed seismic tomographic models and extensive field observations makes the Mediterranean an ideal natural laboratory to study these transfer zones. We review in this paper the various structures in back-arc regions differential retreat from the Alboran Sea to the Aegean-Anatolian region and discuss them with the help of 3D numerical models to better understand the partitioning of deformation between high-angle and low-angle faults, as well as the 3-D kinematics of deformation in the middle and lower crusts. Simple, archetypal, crustal-scale strike-slip faults are in fact rare in these contexts above slab tears. Transfer zones are in general instead wide deformation zones, from several tens to several hundred kilometers. A partitioning of deformation is observed between the upper and the lower crust with low-angle extensional shear zones at depth and complex association of transtensional basins at the surface. In the Western Mediterranean, between the Gulf of Lion and the Valencia basin, transtensional strike-slip faults are associated with syn-rift basins and lower crustal domes elongated in the direction of retreat (a-type domes), associated with massive magmatic intrusions in the lower crust and volcanism at the surface. On the northern side of the Alboran Sea, wide E-W trending strike-slip zones in the brittle field show partitioned thrusting and strike-slip faulting in the external zones of the Betics, and E-W trending metamorphic core complexes in the internal zones, parallel to the main retreat direction with a transition in time from ductile to brittle deformation. On the opposite, the southern margin of the Alboran Sea shows short en-échelon strike-slip faults. Deep structures are not known there. In the Aegean-Anatolian region, two main tear faults with different degrees of maturity are observed. Western Anatolia (Menderes Massif) and the Eastern Aegean Sea evolved above a major left-lateral tear in the Hellenic slab. In the crust, the differential retreat was accommodated mostly by low-angle shear zones with a constant direction of stretching and the formation of a-type high-temperature domes exhumed from the middle and lower crust. These low-angle shear zones evolve through time from ductile to brittle. On the opposite side of the Aegean region, the Corinth and Volos Rift as well as the Kephalonia fault offshore, accommodate the formation of a dextral tear fault. Here, only the brittle crust can be observed, but seismological data suggest low-angle shear zones at depth below the rifts. We discuss the rare occurrence of pure strike-slip faults in these contexts and propose that the high heat flow above the retreating slabs and more especially above slab tears favors a ductile behavior with distributed deformation of the crust and the formation of low-angle shear zones and high-temperature domes. While

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retreat proceeds, aided by tears, true strike-slip fault system may localize and propagate toward the retreating trench, ultimately leading to the formation of new plate boundary, as shown by the example of the North Anatolian Fault.

Keywords: back-arc / transfer faults / STEP-faults / metamorphic core complexes / a-type domes / slab retreat / slab tear / lower crust / magmatism

Résumé – Zones de transfert dans les domaines arrière-arc méditerranéens et déchirures des panneaux plongeants. Les déchirures des panneaux plongeants dans les zones de subduction induisent des déformations localisées dans les domaines arrière-arcs des plaques chevauchantes sous la forme de zones de transfert qui accommodent les différences latérales de vitesse de retrait des fosses. Parce que l'espace disponible pour ce retrait est limité dans le domaine méditerranéen, les déchirures ont joué un rôle majeur dans l'évolution de cette région depuis la fin de l'Eocène. L'association de modèles tomographiques détaillés et de nombreuses observations de terrain font de la Méditerranée un laboratoire naturel idéal pour étudier ces zones de transfert. Nous proposons ici une revue des diverses structures des domaines arrière-arc accommodant le retrait différentiel depuis la Mer d'Alboran jusqu'à la région égéenne et nous les discutons grâce à des modèles numériques 3-D pour mieux comprendre le partitionnement de la déformation entre les failles à fort et faible pendage et la cinématique 3-D dans la croûte moyenne et la croûte inférieure. Nous montrons que les failles localisées purement décrochantes d'échelle crustale sont rares au-dessus de ces zones de déchirure. Les zones de transfert sont au contraire plutôt des zones de déformation larges de quelques dizaines à quelques centaines de kilomètres. On y observe un partitionnement de la déformation entre la croûte supérieure et la croûte inférieure avec des zones de cisaillement extensives à faible pendage en profondeur et une association complexe de bassins en transtension et de détachements dans la croûte supérieure. En Méditerranée occidentale, entre Golfe du Lion et bassin de Valence, des failles décrochantes transtensives sont associées à des bassins syn-rift et des dômes de croûte inférieure allongés dans la direction du retrait (dômes de type « a »), associés à des intrusions magmatiques massives dans la croûte inférieure et du volcanisme en surface. Sur la marge septentrionale de la Mer d'Alboran, des zones décrochantes E-O larges dans le domaine cassant montrent un partitionnement entre des chevauchements et des décrochements dans les zones externes et des dômes métamorphiques allongés E-O dans les zones internes, parallèlement à la direction principale de retrait, avec une évolution du ductile vers le cassant au cours du temps. La rive sud de la Mer d'Alboran montre à l'opposé des failles décrochantes en échelon courtes et les structures profondes sont mal connues. Dans la région Egée-Anatolie, deux zones larges de degré de maturité différents sont observées. L'ouest de l'Anatolie (massif du Menderes) et l'est de la Mer Egée ont évolué au-dessus d'une déchirure majeure du panneau plongeant hellénique. Dans la croûte, le retrait différentiel est principalement accommodé par des zones de cisaillement extensives à faible pendage avec des directions d'étirement cohérentes régionalement et des dômes métamorphiques de type « a » et de haute température exhumés depuis la croûte moyenne et la croûte inférieure. Ces zones de cisaillement à faible pendage évoluent du ductile au cassant au cours du temps. Du côté opposé du domaine égéen, le rift de Corinthe, le rift de Volos, ainsi que la faille de transfert de Céphalonie accommodent la formation d'une large zone de transfert dextre. Dans cette région, seule la croute supérieure peut être observée, mais les données sismologiques suggèrent l'existence de zones de cisaillement à faible pendage sous les rifts actifs. Nous discutons la rareté des grandes failles de transfert purement décrochantes dans ces contextes et proposons que le flux de chaleur élevé au-dessus des panneaux plongeants en recul et plus encore au-dessus des zones de déchirures favorise un comportement ductile avec déformation distribuée de la croûte et la formation de zones de cisaillement à faible pendage et de dômes de haute température. Pendant le retrait, favorisé par ces déchirures, de véritables failles décrochantes lithosphériques peuvent ensuite se localiser et évoluer en limites de plaques, comme le montre l'exemple de la Faille Nord Anatolienne.

Mots clés : arrière-arc / failles de transfert / STEP-faults / metamorphic core complexes / dômes de type « a » / retrait de panneau plongeant / déchirure de panneau plongeant / croûte inférieure / magmatisme

1 Introduction

Slab tears, or STEP-faults (Subduction-Transform-Edge Propagator, from Govers and Wortel, 2005; Wortel *et al.*, 2009), are among the first-order drivers of retreating subduction zones dynamics and thus of deformation in overriding plates. Tearing of wide slabs facilitates back-ward motion of trenches through a reduction of the slab surface and induces the advection of hot and weak asthenosphere in the slab window with thermal and thus rheological impacts on the upper plate (Carminati *et al.*, 1998b; Faccenna *et al.*, 2006; Piromallo *et al.*, 2006; Schellart *et al.*, 2007; Sternai *et al.*, 2014; Jolivet *et al.*, 2015b). 3-D thermo-mechanical numerical models have explored the impact of slab tears on the deformation in back-arc domains and they all suggest drastic consequences in terms of migration of magmatism and strain localization that can be compared to natural environments at regional (Sternai *et al.*, 2014; Menant *et al.*, 2016b) or crustal scale (Le Pourhiet *et al.*, 2012). But a systematic description of structures at different scales in the back-arc region related to slab tearing and their evolution is not yet available. These structures form within zones of variable width transferring deformation between domains of different amounts of retreat and magnitude of stretching in the overriding plate. In this study, we explore the crustal response of the overriding plate above a slab tear, how the crust accommodates the formation of the STEP-fault in the subducting lithosphere underneath. By STEP-faults or tear faults we refer to a fault in the slab accommodating tearing (Govers and Wortel, 2005; Wortel *et al.*, 2009). The expression of that fault in the overriding lithosphere and crust is called here a transfer fault or a transfer zone.

Transfer faults are common features of rift systems (Gibbs, 1984, 1990; Colletta *et al.*, 1987; Chorowicz, 2005). They accommodate lateral differences in extension rates or differences in extensional structures geometry, such as different sense of block tilting such as in the Suez Rift (Colletta *et al.*, 1987) or in the Rhine Graben (Brun *et al.*, 1991, 1992). They are either strictly parallel to the regional stretching directions, in which case simple geometrical rules link the steep normal faults, the detachments and the strike-slip faults (Gibbs, 1990), or oblique if they are reactivated structures (Colletta *et al.*, 1987). Faults striking parallel to the regional direction of extension are often not pure strike-slip discontinuities and they show instead a significant dip-slip component (Faccenna *et al.*, 1994). The Mediterranean back-arc regions offer the opportunity of studying both the upper crustal and lower crustal expressions of these transfer zones, thanks to the exhumation of lower crust domains in metamorphic core complexes and a wealth of seismic profiles.

The driving mechanisms of extension might be entirely different between back-arc regions and intra-continental rifts such as the Suez rift of the East African Rift, but it remains that back-arc rifts are also segmented by transfer faults or transfer zones. Although the Liguro-Provençal basin, the Algerian basin and the Valencia basin were formed above a retreating subduction zone, they bear strong similarities with intra-continental rifts and they have evolved into passive margins with many characteristics of Atlantic-type passive margins. It is thus worth discussing the related transfer zones and compare them to those segmenting classical rift zones. They have in addition intimate links with the behavior of the retreating slab and more specifically to slab tears that introduce longitudinal variations of the velocity of slab retreat.

Such transfer zones are indeed particularly well expressed in the Mediterranean realm (Figs. 1 and 2) where subduction zones were segmented by several episodes of slab tearing since the Late Eocene because of the irregular shape of the European and North African margins of the Tethys Ocean (Carminati *et al.*, 1998b; Jolivet and Faccenna, 2000; Wortel and Spakman, 2000; Spakman and Wortel, 2004; Hafkenscheid *et al.*, 2006; van Hinsbergen *et al.*, 2014; Menant *et al.*, 2016a; Romagny *et al.*, 2020). The Mediterranean Sea is heir of the Neo-Tethys Ocean but the dynamics of subduction changed drastically some 30–35 Ma ago when the typical Mediterranean dynamics started (Jolivet and Faccenna, 2000). Before 30–35 Ma in this region, mountain belts such as the Hellenides were formed in the overriding plate by subduction of continental fragments such as Apulia (Adria). At the end of the Eocene, the subduction regime changed and pieces of slabs started to retreat, leading to the formation of back-arc basins and collapse of the mountain belts. After 35 Ma the Mediterranean subductions thus started to retreat at different rates depending upon the width of the slab, which imposes variable extension rates along strike and induces the formation of transfer zones. Other favorable situations for the formation of slab tears are contacts between oceanic and continental crust in the subducting lithosphere.

A wealth of detailed studies of the Mediterranean back-arcs has been accumulating since about 20 years and we summarize the main observations in this paper, focusing on the crustal sections lying above major slab tears. We then discuss their implications in terms of crustal rheology and coupling between mantle flow and crustal deformation. We show that simple strike-slip faults are not frequent, much less so than low-angle extensional faults and ductile shear zones. We also show how the deformation may progressively localize until the eventual formation of a new plate boundary.

2 Geological and geodynamic context

From the Alboran Sea in the west to the Aegean Sea in the east, the Mediterranean back-arc basins share a common timing but differ by the directions and velocities of extension (Fig. 2) (Jolivet and Faccenna, 2000; Faccenna *et al.*, 2004, 2014; Govers and Wortel, 2005; Jolivet *et al.*, 2009; Wortel *et al.*, 2009). The main episode of back-arc extension started at the Eocene-Oligocene transition, between 35 and 30 Ma. Evidence for an earlier extension is found in the West European Rift as soon as the Priabonian (Séranne, 1999; Dèzes *et al.*, 2004; Séranne *et al.*, 2019), but the geometry of the rift system shows that it is not a direct consequence of slab retreat. Several mechanisms were proposed, including the activity of a mantle upwelling below Western Europe or a consequence of the Alpine orogeny with a downward flexure of the European plate subducting below the orogen (Hoernle *et al.*, 1995; Goes *et al.*, 1999; Merle and Michon, 2001; Ziegler and Dèzes, 2005).

The evolution of the Western and Central Mediterranean shows a progressive migration of extension from the Spanish and French coastal regions with the opening of the Liguro-Provençal basin and then the southeastern Tyrrhenian Sea from the Oligocene to recent times (Réhault *et al.*, 1984, 1987; Kastens *et al.*, 1988; Carminati *et al.*, 1998a; Faccenna *et al.*, 2001a, 2001b). The evolution of the Tyrrhenian Sea in particular reveals a migration of extension from west to east and progressive crustal thinning from the Miocene to the Present due to the retreat of the Ionian slab (Kastens *et al.*, 1988). The Alboran Sea results from a succession of two episodes of extension, first N-S and then E-W, with a westward migration of the arc following retreat of the slab underneath Gibraltar during the second period after ∼ 8 Ma (Crespo Blanc, 1995; Martinez-Martinez and Azañon, 1997; Wortel and Spakman, 2000; Faccenna *et al.*, 2004; Jolivet *et al.*, 2006, 2008; Crespo-Blanc *et al.*, 2016). In the Eastern Mediterranean region, southward retreat of the Hellenic slab led to the collapse of the Hellenides and rifting of the Aegean Sea (Le Pichon and Angelier, 1981; Brun and Faccenna, 2008; Ring *et al.*, 2010; Jolivet *et al.*, 2013). Extension started earlier in the Rhodope Massif as soon as 40–45 Ma with the beginning of formation of a large metamorphic core complex (MCC)

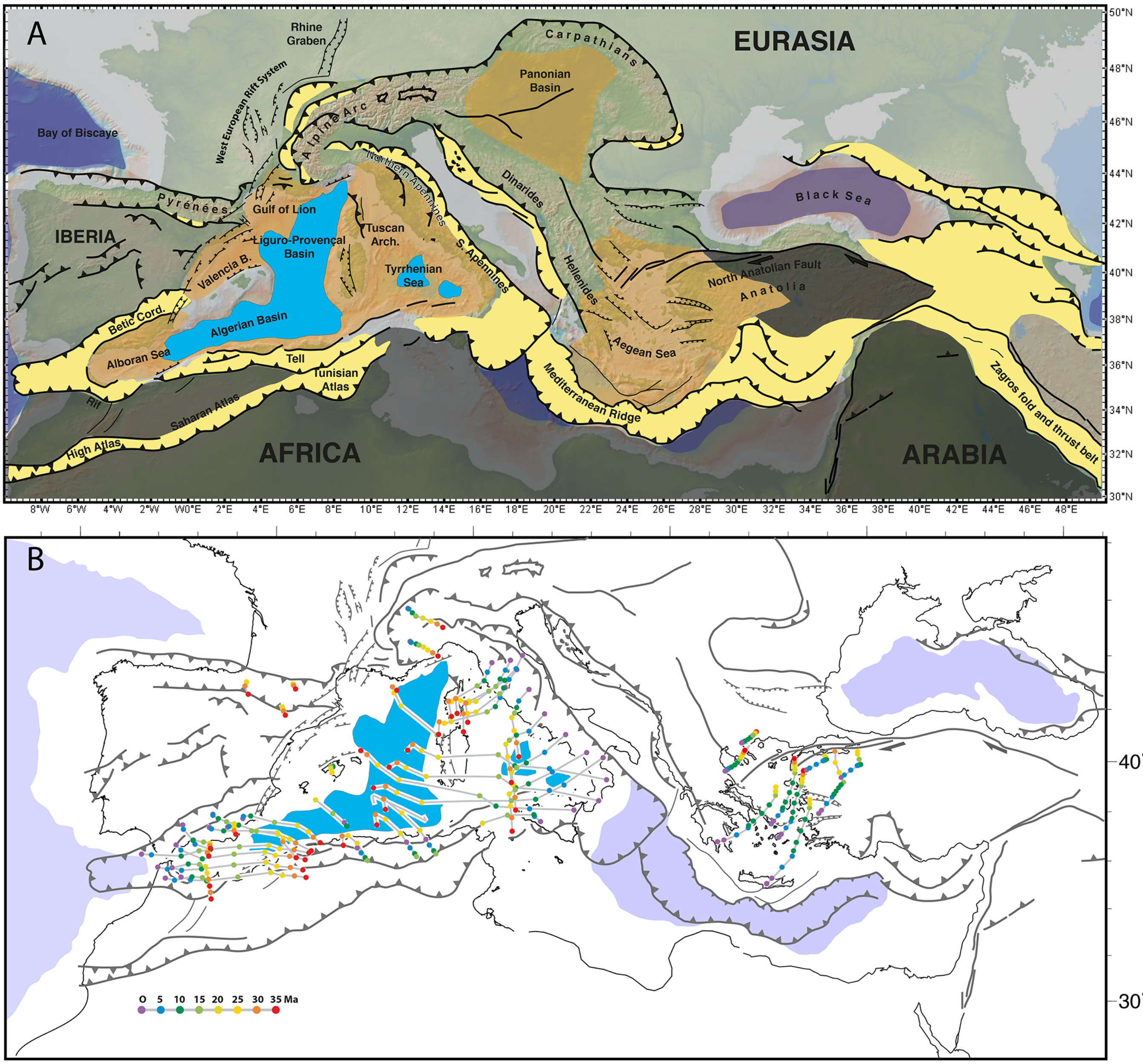

Fig. 1. Tectonic map of the Mediterranean region and displacements in back-arc regions since 35 Ma. A: Tectonic map of the Mediterranean showing the main mountain belts and basins and the large and small plates. B: Motion paths of crustal blocks in the Mediterranean back-arc basins after Menant *et al.* (2016a, 2016b) and Romagny *et al.* (2020). Crossing paths in the South Tyrrhenian Sea region are due to three main reasons as explained in details in Romagny *et al.* (2020): (1) the motion paths shown in this figure do not represent an instantaneous velocity field, which would forbid such crossings, but the full paths of each point, (2) the two sets of crossing paths corresponds to two very different origins for the moving points, (i) points initially belonging to Apulia (Adria) and moving first together with Africa northward and then recording the opening of the South Tyrrhenian Sea, thus northeastward and (ii) points initially belonging to the AlKaPeCa block and moving eastward all along since 30 Ma because they follow the rotation of the Corsica-Sardinia block during the opening of the Liguro-Provençal basin and then the opening of the Southern Tyrrhenian Sea. When the latter points reach the longitude of the present-day Southern Tyrrhenian Sea the other points are already further north and there is no "collision" (Romagny *et al.*, 2020 show this kinematics in details, see the full movie of the reconstructions in the supplementary material of that paper), (3) the crossings are also partly due to the facts that some of these moving points selected for drawing Figure 1 correspond to thrust front of the Ligurian domain that has overthrust the Tuscan domain; these points thus move further eastward and their paths then cross that of the points belonging to the Tuscan domain.

(Brun and Sokoutis, 2007; Burg, 2012), an interpretation challenged by Gautier *et al.* (2017). The Rhodope MCC formed coeval with the subduction of the Pindos Ocean and its continental margin (the Cycladic Blueschists, CBS) and is associated with high-temperature and low-pressure metamorphic facies contrasting with the blueschists and eclogites of the

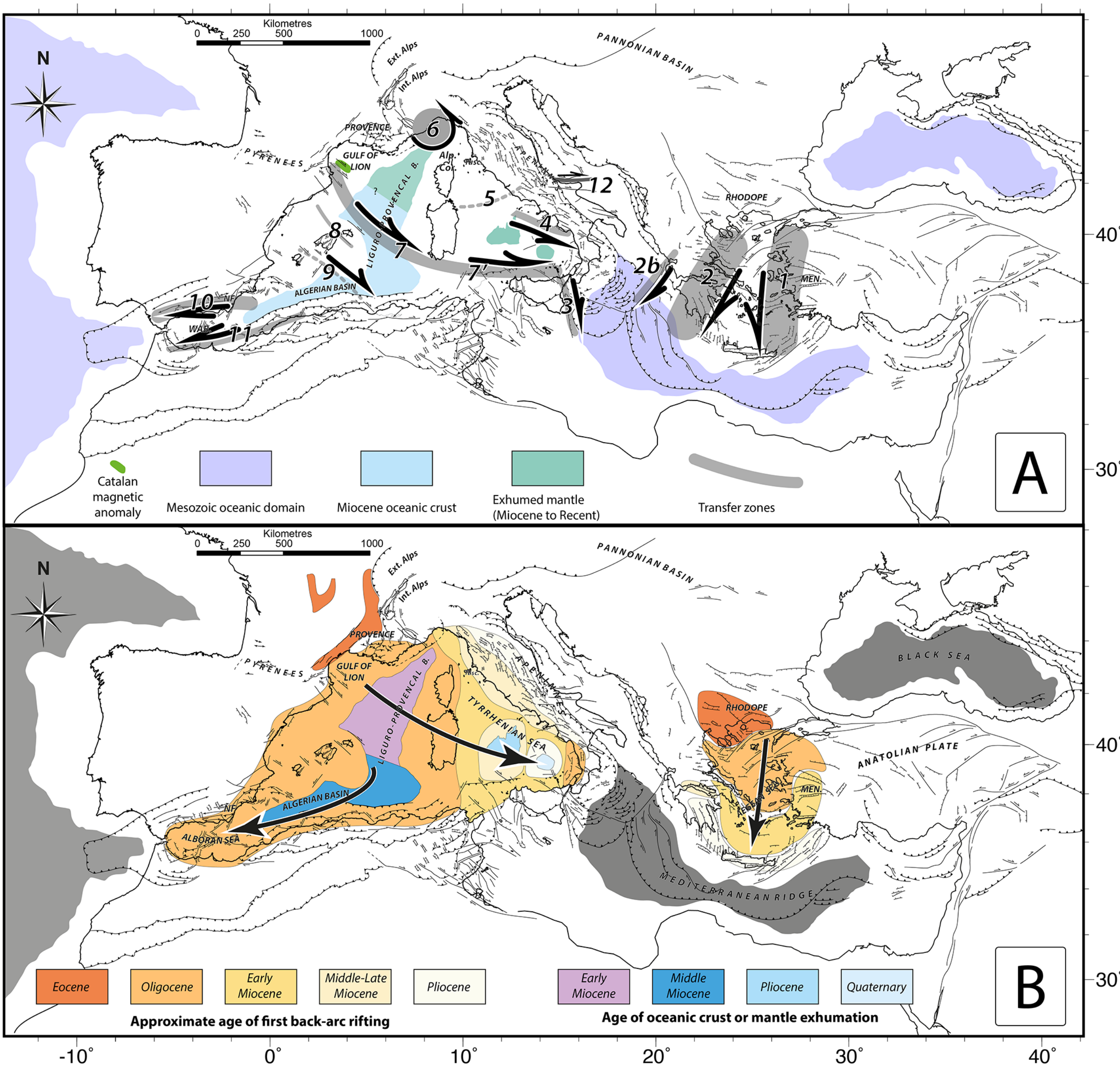

Fig. 2. Transfer zones and timing of extension in Mediterranean back-arc basins. A: location of transfer zones discussed in the text (thick grey lines or domains). Nature of oceanic floor: exhumed mantle domains after Prada *et al.* (2014, 2016, 2018) and Dannowski *et al.* (2019a, 2019b). B: Timing of rifting and emplacement of oceanic crust. 1: West Anatolia Transfer Zone, 2: Central Aegean Shear Zone, 2b: Kephalonia transfer fault; 3: western limit of the Calabria accretionary wedge, 4: transfer zone along the northern limit of the Southern Tyrrhenian oceanic/exhumed mantle domain, 5: 41st parallel fault, 6: Alps/Apennines transition, 7: Catalan-Baleares)Sicily Transfer Zone (CBSTZ), 8: Central transfer zone (Valencia basin), 9: transition between the Liguro-Provençal and Algerian basins, 10: Betic Cordillera, northern limit of the Alboran Sea, 11: Rif, southern limit of the Alboran Sea, 12: Trimiti transfer zone.

CBS (Krohe and Mposkos, 2002; Brun and Faccenna, 2008; Jolivet and Brun, 2010). In that period, the position of the magmatic arc has been relatively stable at the latitude of the Balkans since the Late Cretaceous and remained stable there until ~ 30 Ma when it started its southward motion, coeval with the Aegean Sea extension (Jolivet *et al.*, 2004; Jolivet and Brun, 2010). Before 30 Ma, no significant crustal thinning is observed and no migration of the volcanic arc either, showing that extension in the Rhodope around 40 Ma is not driven by a major slab retreat. Extension in the Aegean Sea after ~ 35 Ma induced the exhumation of the Cycladic MCCs under low-angle detachments, the North Cycladic Detachment System (NCDS), the West Cycladic Detachment System (WCDS), the Paros-Naxos Fault System (NPFS) and the South Cycladic Detachment (SCD) (Jolivet *et al.*, 2010; Grasemann *et al.*, 2012; Bargnesi *et al.*, 2013; Schneider *et al.*, 2018).

Several changes in the deformation of these back-arc domains are recorded in the geology. One major event started at around 20 Ma and lasted until about 8 Ma. It corresponds to several tearing episodes in the Mediterranean slabs (van Hinsbergen *et al.*, 2005; Jolivet *et al.*, 2013, 2015b). In the Aegean, the eastern Aegean transfer zone, or West Anatolian Transfer Zone (WATZ) (transfer zone #1 on Fig. 2a) formed during this period accommodating the fast rotation of the western arm of the Hellenic arc (Kissel and Laj, 1988; Kissel *et al.*, 2003; van Hinsbergen *et al.*, 2005). In the Central and Western Mediterranean, this period corresponds to the separation of the subducting slab in two main segments, one retreating eastward and one westward (Fig. 2b) (Lonergan and White, 1997; Rosenbaum *et al.*, 2002; van Hinsbergen *et al.*, 2014; Leprêtre *et al.*, 2018; Romagny *et al.*, 2020). 8 Ma is another major change in the kinematics. In the Western Mediterranean, the E-W extension active until then was replaced by the renewal of the N-S compression that progressively invaded the whole back-arc domain, including the southern Tyrrhenian in the late Pliocene (Billi *et al.*, 2011; Zitellini *et al.*, 2019).

From 35 Ma onward, back-arc rifting migrates southward in the Aegean together with the volcanic arc (Jolivet and Brun, 2010). It migrates eastward and southeastward in the Liguro-Provençal Basin and Tyrrhenian Sea and southward and then westward in the Algerian Basin and Alboran Sea (van Hinsbergen *et al.*, 2014; Leprêtre *et al.*, 2018). Through this period, the rifting basin in the Central Mediterranean narrows considerably as the slab is progressively torn (Carminati *et al.*, 1998b; Faccenna *et al.*, 2007). Kinematic reconstructions show fuzzy discontinuities in the displacement field which are accommodated by transfer zones (Fig. 2). Some are narrower than others and some are very wide.

The best example of a wide transfer zone is the West Anatolian Transfer Zone (Ring *et al.*, 1999; Gessner *et al.*, 2013; Roche *et al.*, 2019) in the eastern Aegean (transfer zone #1 on Fig. 2). It accommodates the differential extension between Anatolia and the central Aegean Sea where extension reaches its maximum. It is distributed across a wide zone encompassing the Menderes Massif, the Dodecanese and the Eastern Aegean Islands and part of the Cyclades. The relative motion is mainly accommodated by a series of detachments with the top-to-the north motion and corresponds to a lateral gradient of extension rather than a pure strike-slip system (Roche *et al.*, 2019). It is named the West Anatolian Transfer Zone by Gessner *et al.* (2013). It sits on top of a major discontinuity in the Hellenic slab recognized in the tomographic models (de Boorder *et al.*, 1998; Wortel and Spakman, 2000; Biryol *et al.*, 2011; Salaün *et al.*, 2012; Govers and Fichtner, 2016). Another wide transfer zone is #2 in the onshore prolongation of the North Aegean Trough. It has been recognized as a wide strike-slip zone by various authors and most recently by Royden and Papanikolaou (2011). It includes several large rifts perpendicular to its strike, the Volos rift and the Corinth Rift and a series of normal faults within the Peloponnese. It extends all the way to the trench with the Kephalonia Fault (#2b) (Pérouse *et al.*, 2012, 2017). It is located above an immature tear in the Hellenic slab recognized in recent tomographic models and receiver functions seismic profiles (Suckale *et al.*, 2009; Sachpazi *et al.*, 2016).

Transfer zone #3 limits the Calabrian accretionary wedge to the west (Gutscher *et al.*, 2017) and is thus not located in the back-arc domain. Transfer zone #4 is a complex and wide shear zone separating during the Pliocene and the recent period the extending southeast Tyrrhenian Sea from the mainland of southern Italy (Milia *et al.*, 2017). Transfer zone #5 grossly corresponds to the boundary between the southern and northern Tyrrhenian Sea. It marks the northern limit of the oceanic domain and highly extended crust of the southern Tyrrhenian Sea and the less extended northern Tyrrhenian Sea. It has long been enigmatic and it was described as a left-lateral strike-fault localized along the 41st parallel (Boccaletti *et al.*, 1990; Bruno *et al.*, 2000) but in fact it does not exist as a real strike-slip fault zone. Offshore studies showed a more complex association of normal and minor strike-slip faults and a migration of extension through time (Spadini and Wezel, 1994; Mascle and Chaumillon, 1997) and other faults with a NW-SE strike (*i.e.* Solenzara Fault on Fig. 5) can be proposed for accommodating differential extension during the Late Miocene slab retreat (Thinon *et al.*, 2016). Transfer zone #6 is a complex one, which geometry is not known. It accommodates the transition between the westward Apennine subduction and the eastward Alpine subduction and the coeval counter-clockwise rotation of the Alps, the Northern Apennines and the Corsica-Sardinia block (Maffione *et al.*, 2008; Vignaroli *et al.*, 2008). It encompasses the whole transition between the Alps and the Apennines in Liguria and is more a wide accommodation zone than a proper transfer zone. It has long been suspected to represent complex interactions between the crust and the flowing mantle at a time when no tomographic models were available and mantle dynamics not understood to circumvent apparent inconsistencies with the plate tectonics model, see the works of van Bemmelen (1973, 1974) or the "spiral tectonics" of Caire (1974).

Transfer zone #7 is the longest in the Mediterranean. Running from the eastern end of the Pyrenees at their junction with Gulf of Lion to the northern side of Sicily, it goes along the northeastern end of the Baleares and south of Sardinia. We name it the Catalan-Baleares-Sicily Transfer Zone (CBSTZ) in the following. It groups several transfer faults already described in the literature such as the Catalan Fracture Zone (Mauffret *et al.*, 1995). It accommodates the progressive rotation of the Corsica-Sardinia block and then the progressive opening of the southern Tyrrhenian Sea. It starts east of the Pyrenees as the Catalan Fracture Zone (CFZ) and then the North Baleares transfer zone (NBTZ) (Mauffret *et al.*, 1995; Séranne, 1999) and reaches the north of Sicily where it is currently reactivated by N-S compression. Sometimes known as the Accident Paul Fallot (Durand-Delga and Fontboté, 1980), it was not precisely described until recently. Recent studies show its geometry in its northern part at the limit between the Gulf of Lion and the Pyrenees and the Valencia Basin (Maillard *et al.*, 2020). The total relative motion accommodated through this shear zone amounts to 800 km at its southeasternmost end (Romagny *et al.*, 2020) (Fig. 1). One characteristic of these transfer zones is indeed that the amount of relative displacement increases along strike, no displacement at the northern tip of the Catalan transfer fault and several hundred at the southeastern termination. Transfer Fault #8 is a satellite of #7. The transition between the Valencia Basin and the Gulf of Lion is accommodated by several parallel dextral faults associated with magmatism (Pellen *et al.*, 2016; Maillard *et al.*, 2020).

Transfer zone #9 marks the transition with the domain where the kinematics of extension is mostly E-W in the reconstructions. Its position strongly depends upon the details of the reconstructions (Vergés and Fernàndez, 2012; Romagny *et al.*, 2020). Depending upon the size and distribution of moving blocks it will be wide or narrow and its exact position depends upon the kinematics of the different Balearic islands during extension. No known structure is associated with this transfer zone. Finally, transfer zones #10 and #11 limit the Alboran Sea to the north and the south, accommodating the westward motion of the Alboran block since the early Miocene (Frizon de Lamotte *et al.*, 1991). In the north, the transfer zone is as wide as the internal zones of the Betic Cordillera and the dextral motion is accommodated by a mixture of low-angle normal faults and some strike-slip faults (Frasca *et al.*, 2015; Romagny *et al.*, 2020). In the south, a series of en-échelon left-lateral strike-slip faults accommodate the relative motion in the West Algerian basin (Medaouri *et al.*, 2014) and two left-lateral shear zones in the Rif Cordillera known as the Nekor and Jebha fault zones (Benmakhlouf *et al.*, 2012; Booth-Rea *et al.*, 2012).

Some transfer zones have been described in the subducting plate such as TZ#3 bounding the Calabria accretionary wedge to the west (Gutscher *et al.*, 2017) or the Tremiti transfer zone (#12) separating two segments of the subducting Adriatic plate (Scrocca, 2006). Although their expression is clear they are not located within the overriding plate and are thus outside the scope of this paper.

In the following we describe the structures observed across some of these transfer zones.

3 Transfer zones in the Liguro-Provençal Basin and Tyrrhenian Sea

We focus this description on some recent discoveries made along the Catalan-Baleares-Sicily Transfer Zone (CBSTZ, #7), essentially in its northern part and on transfer zones in the Tyrrhenian Sea (#4).

3.1 Transfer zones between Valencia Basin and Gulf of Lion

The abrupt termination of the Pyrenees against the Gulf of Lion passive margin requires the presence of a transfer zone, named the Catalan Fracture Zone (CFZ) (Mauffret *et al.*, 2001) or the North Baleares Transfer Zone (Séranne, 1999) (Fig. 3). Initially placed there for kinematic reasons, it was described as the western limit of a series of tilted blocks and SE-dipping listric faults with progressive crustal thinning toward the SE (Mauffret *et al.*, 2001) and it has an extensional component. A series a recent studies shed some new light on this structure (Canva *et al.*, 2020; Maillard *et al.*, 2020). One of the most prominent geophysical features of this region is the so-called Catalan magnetic anomaly (Guennoc *et al.*, 1994; Canva *et al.*, 2020) (Figs. 2 and 3 inset). It is located at some distance of the eastern coastline of the Pyrenees and strikes parallel to the CFZ. It corresponds to a strong magnetic anomaly without a significant expression in the gravity field. Modelling shows that it is probably due to the presence of large body of mafic rocks (gabbros) intruded in a thinned continental crust and underplated at its base (Canva *et al.*, 2020). This could come as a surprise as the Gulf of Lion passive margin is characterized by the absence of significant volcanic material, except for a small syn-rift volcano identified on reflection profile RM-208 (Jolivet *et al.*, 2015a). In fact, the CFZ/NBTZ delimits the Gulf of Lion from the Valencia Basin which, in the opposite, shows thick syn-rift volcanic deposits within a large province (Maillard and Mauffret, 1999; Maillard *et al.*, 2020). This intense volcanic episode has led to the formation of a thick volcanic layer, with a variable thickness between 1 and 3 km and individual volcanic edifices arranged en-échelon along N-S-SE trending fracture zones parallel to the CFZ (Figs. 3 and 4). This volcanic province was already described by Mauffret *et al.* (1995) and Maillard and Mauffret (1999) with vintage seismic reflection lines, but the analysis of more recent profiles shows the detailed geometry of this volcanic layer and its distribution across a wide zone (Maillard *et al.*, 2020).

Several other NW-SE trending fault zones are reported (Fig. 3), including the North Baleares Fracture Zone (Maillard and Mauffret, 1999; Mauffret *et al.*, 2001; Pellen *et al.*, 2016; Maillard *et al.*, 2020). The analysis of seismic profiles also shows distinct structures within the crust (Maillard *et al.*, 2020). Syn-rift grabens or half-grabens are filled with the syn-rift sedimentary sequences on top of the syn-rift volcanic layer (Fig. 4). The deepest among these grabens are restricted to the vicinity of the CFZ/NBTZ and are transtensional basins accommodating the dextral deformation in the upper crust during rifting. Below these grabens, the crust appears stratified, with a transparent upper crust and a more reflective lower crust, see Fig. 11 in Maillard *et al.* (2020). The interfaces between these different crustal layers are undulated and show domes of lower crust and/or upper mantle with low-angle prominent reflectors that are interpreted as low-angle extensional shear zones. In 3-D, these domes are elongated parallel to the strike of the CFZ, and thus parallel to the relative motion, making them a-type extensional domes (Jolivet *et al.*, 2004) (Fig. 4), thus compatible with a component of strike-slip shearing during extension (Le Pourhiet *et al.*, 2012). The nature of the lower crust and the exact position of the Moho is debatable as the lower crust reveals high P-waves velocities intermediate between that of the mantle and that of a normal lower crust, around 7 or 7.2 km/s. This type of high-velocities is reminiscent of the distal domain of the Gulf of Lion margin which has been interpreted as lower crustal material partly intruded by mafic volcanism (Gailler *et al.*, 2009; Jolivet *et al.*, 2015a, 2019; Moulin *et al.*, 2015). This would make a clear link with the gabbroic material underplated below the CFZ further to the NW (Canva *et al.*, 2020). This example shows a partitioning of deformation between the upper and lower crusts. The upper crust shows transtensional faults and sedimentary basins while the lower crust and the mantle show low-angle shear zones connected to the upper crustal faults.

The Catalan Fracture Zone and the North Baleares Fracture Zone thus make a set of faults with distinct crustal-scale features, including transtensional syn-rift basins and a-type lower crustal domes and a large amount of magmatism, either restricted to the lower crust or extruding at the surface during rifting making a large volcanic province. The contrast with the non-volcanic Gulf of Lion margin is striking, but in both cases the lower crust deforms ductilely and makes lower crustal domes.

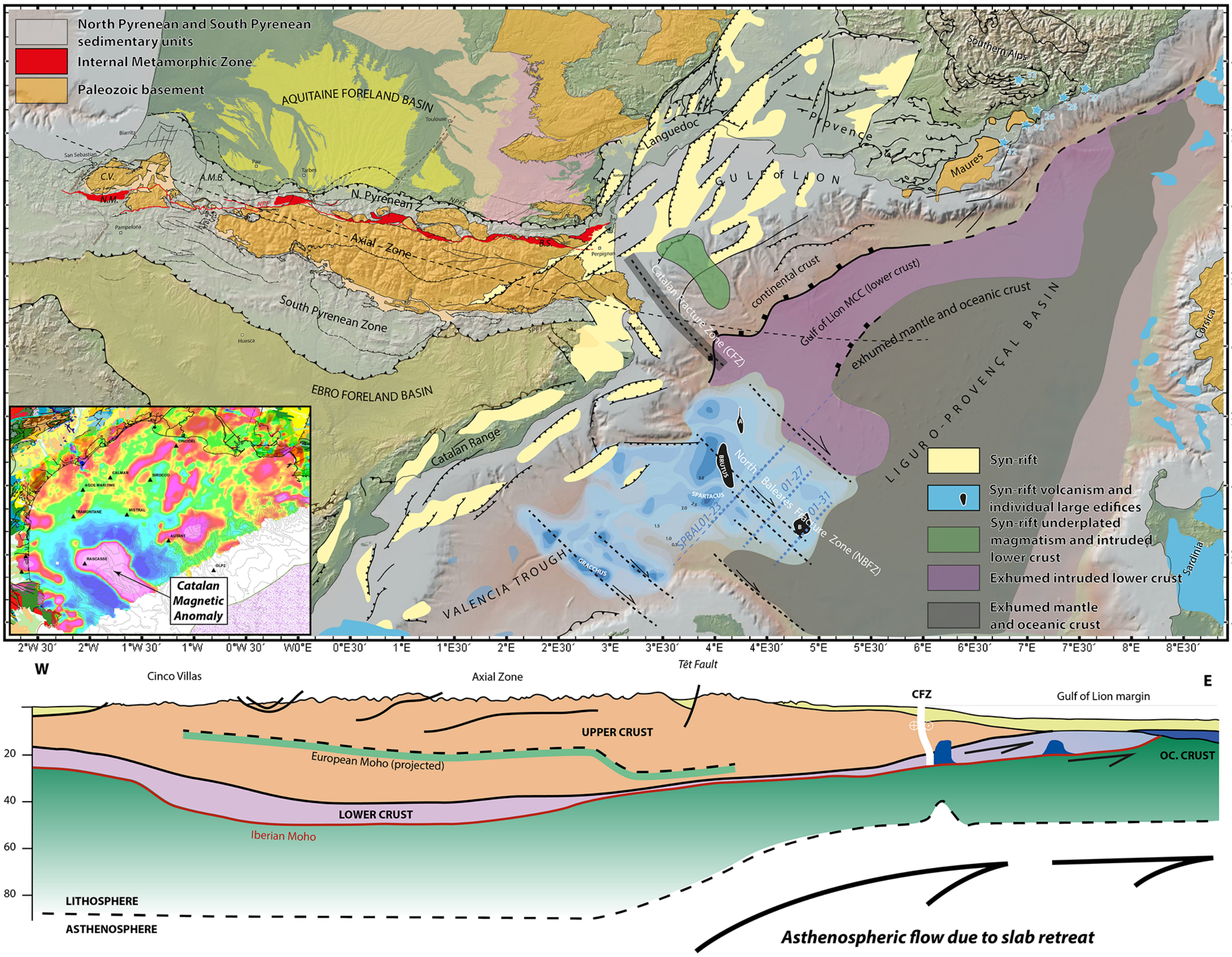

Fig. 3. Structural map of the Gulf of Lion, northeast Valencia Basin and Pyrenees and a along-strike cross-section from the Pyrenees to the Gulf of Lion. After Roca and Guimerà (1992), Jolivet *et al.* (2019), Canva *et al.* (2020) and Maillard *et al.* (2020). Bathymetry and topography from GeoMapApp (Ryan *et al.*, 2009).

3.2 The CBSTZ

The CFZ and the NBFZ make the northwestern part of a large transfer zone (CBSTZ #7) that accommodated the rotation of the Corsica-Sardinia Block and then the rotation of the Italian Peninsula during the opening of the Tyrrhenian Sea (Fig. 2). Although the transfer zone is necessary on kinematic grounds its structural expression is unknown along most of its length. The main structures visible in the Sardinia Channel and north of Sicily are more recent features associated with the N-S compressional reactivation (Tricart *et al.*, 1994; Sulli, 2000; Mascle *et al.*, 2004; Catalano *et al.*, 2013) (Fig. 5). Some strike-slip system might seem necessary north of Sicily, along the present-day Eolian arc to accommodate the relative motion of Sicily with respect to Sardinia and the Vavilov and Marsili basins, but they have not been found. Instead, a fan-shaped system of roughly N-S trending normal faults is described by Milia *et al.* (2018). On the opposite, the evolution of the NE side of the Tyrrhenian Sea is much better known thanks to recent contributions (Conti *et al.*, 2017; Milia *et al.*, 2017). The long-term evolution of this region shows a progressive narrowing of the back-arc basin during the eastward migration and the successive rifting of the Cornaglia Terrace (labelled 1 on Fig. 5), Vavilov basin (2) and Marsili basin(3) (Carminati *et al.*, 1998b; Faccenna *et al.*, 2007; Wortel *et al.*, 2009).

The CBSTZ links the transfer zones that segment the Liguro-Provençal rift system (CBZ and NBFZ) and thus accommodating the rigid rotation of the Corsica-Sardinia block with the transfer zone accommodating the rotation of the Italian peninsula. The geodynamic evolution of this region shows a continuum of slab retreat and back-arc opening from the Oligocene to the Present with a migration from the Provence region to the present-day southern Tyrrhenian Sea. Slower extension was recorded between 15 and 10 Ma, but otherwise the process was continuous (Faccenna *et al.*, 2001a, 2001b). The rotation has been accommodated by a large-scale transfer zone, the CBSTZ, which has been first active in the NW and then in the SE. It was not active along its trace at the same time but, instead, deformation has migrated toward the southeast. It is a wide structure with several parallel faults in its northwestern segment. It appears as a series of parallel transfer faults in the northwest, segmenting the Liguro-Provençal

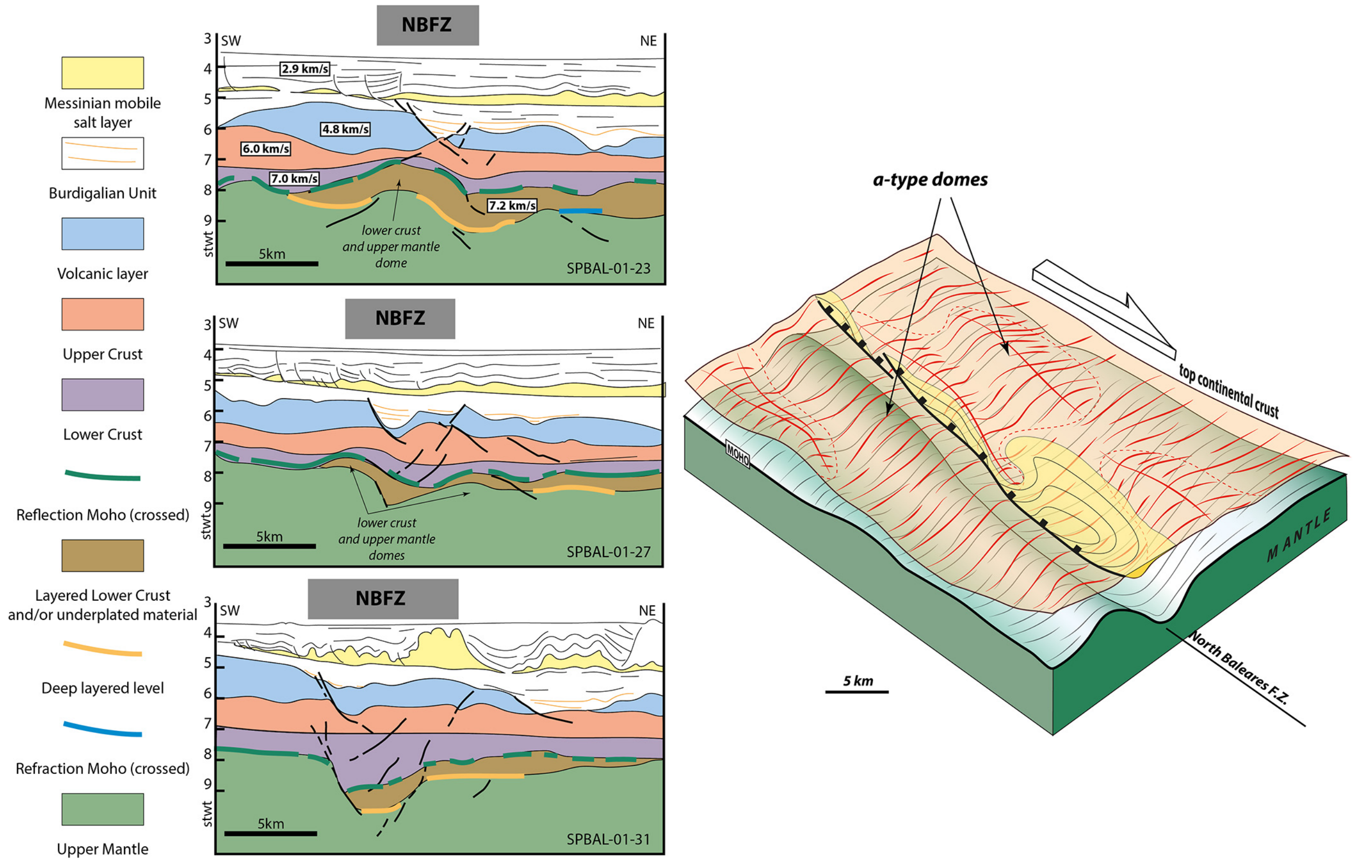

Fig. 4. Interpretation of three seismic profiles across the North Baleares Fracture Zone, modified after Figure 11 of Maillard et al. (2020) and a 3-D diagram schematizing the geometry of the Moho and the top of the crust, showing domes elongated parallel to the transfer zone.

back-arc rift system. This large fault system is the response of the overriding lithosphere to the differential retreat of the slab on either side. A first order slab tear started to form in the NW near the Provençal coast of France, an event that is also marked by the occurrence of adakitic magmatism in the late Eocene and early Oligocene (Réhault *et al.*, 2012).

3.3 Transfer zones and the Tyrrhenian Sea

The present-day dynamics of this region is mostly controlled by the recent N-S shortening encompassing most of the Western and Central Mediterranean, although the transition from back-arc extension to N-S compression is probably very recent (Billi *et al.*, 2007, 2011; Presti *et al.*, 2013; Zitellini *et al.*, 2019). The structure of the Calabrian accretionary wedge is however largely dictated by the geometry of the slab underneath with a right-lateral transfer fault along its western termination along the Malta escarpment (#3 on Fig. 2a) (Polonia *et al.*, 2016; Gutscher *et al.*, 2017) (Fig. 5). This fault connects northward with the Tindari fault, a system of dextral faults connecting the Etna volcano with the Eolian Arc (Billi *et al.*, 2006; Loreto *et al.*, 2019). It marks the transition between the well-developed compressional system to the west and a system dominated by extension to the east (Billi *et al.*, 2006).

In the Northern Tyrrhenian Sea, finite extension and crustal thinning increase toward the south, but no first-order transfer faults have been found to account for this variation. The extensional deformation dates back to the Oligocene in the Tyrrhenian Sea with evidence of ductile and brittle extension in Corsica (Jolivet *et al.*, 1990, 1998; Brunet *et al.*, 2000) and in Calabria (Rossetti *et al.*, 2001, 2004) but most of it is more recent, from the Early and Middle Miocene to the Present (Kastens *et al.*, 1988; Patacca *et al.*, 1990; Sartori, 1990, 2003; Sartori *et al.*, 2004). In the Northern Tyrrhenian Sea (Fig. 5), a clear migration of syn-rift basins, metamorphic core complexes and syn-kinematic magmatism is observed, starting in the Oligocene in Corsica and reaching the Apennines in the Pliocene (Jolivet *et al.*, 1998). The direction of extension is parallel to the transect and no significant strike-slip system is recognized. NW-SE trending faults such as the Solenzara Fault (Fig. 5) (Thinon *et al.*, 2016) could have partly accommodated lateral variations of finite extension. This fault is observed offshore controlling the Messinian deposits and extending the onshore Saint Antoine fault, a normal fault with a strike-slip component with 4 km of vertical offset since the Burdigalian (Mauffret *et al.*, 1999; Loÿe-Pilot *et al.*, 2004). In Elba island, where the dominant deformation is accommodated by low-angle east-dipping detachments such as the Zuccale Fault or the ductile shear zone accommodating the exhumation of Monte Capanne pluton (Keller and Pialli, 1990; Daniel and Jolivet, 1995; Jolivet *et al.*, 1998; Collettini and Holdsworth, 2004), minor transfer faults offset the main detachment and are active during the same tectonic episode. These transfer faults

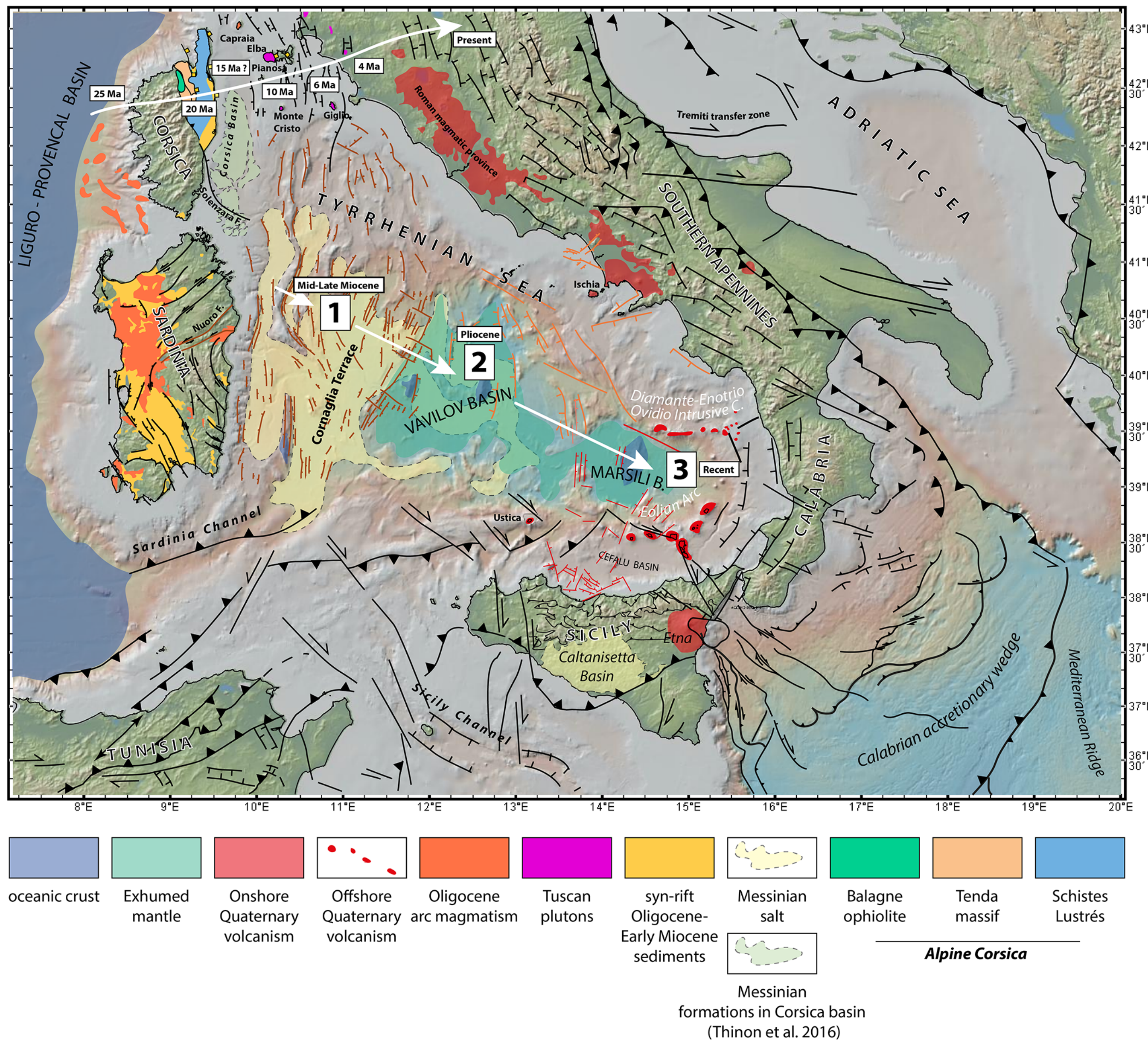

Fig. 5. Compiled structural map of the Tyrrhenian Sea and surrounding regions (Jolivet *et al.*, 1990, 1998; Keller and Pialli, 1990; Roure *et al.*, 1990; Daniel and Jolivet, 1995; Mascle and Chaumillon, 1997; Brunet *et al.*, 2000; Bruno *et al.*, 2000; Collettini and Holdsworth, 2004; Sartori *et al.*, 2004; Billi *et al.*, 2006, 2007, 2011; Catalano *et al.*, 2013; Presti *et al.*, 2013; Prada *et al.*, 2014, 2016, 2018; Gasparo Morticelli *et al.*, 2015; Liotta *et al.*, 2015; Lymer *et al.*, 2016; Polonia *et al.*, 2016; Thinon *et al.*, 2016; Conti *et al.*, 2017; Gutscher *et al.*, 2017; Milia *et al.*, 2018; De Ritis *et al.*, 2019; Loreto *et al.*, 2019; Zitellini *et al.*, 2019; Haq *et al.*, 2020). Bathymetry and topography from GeoMapApp (Ryan *et al.*, 2009).

allow fluid circulation and the associated mineralization (Liotta *et al.*, 2015) like in active geothermal systems set on large-scale detachments (Faulds *et al.*, 2009; Roche *et al.*, 2018a, 2018b). These faults are second-order features, not transfer faults at crustal or lithospheric scale.

The transition with the southern Tyrrhenian Sea is achieved by an increasing number of NW striking normal faults and few faults with a strike-slip component (Fig. 5). This transition region was classically associated with the "41st parallel fault" (Boccaletti *et al.*, 1990), a strike-slip faults system essentially designed for kinematic compatibility. But, more recent bathymetric maps and seismic investigations show instead a more progressive transition with predominant normal faulting (Mascle and Chaumillon, 1997). The large difference in the finite rate of extension between the deep domain of the Tyrrhenian Sea where oceanic crust and/or exhumed mantle have been emplaced and the Italian peninsula imposes the presence of an accommodation zone in-between, hence our TZ#4. Seismic offshore investigation near the Italian coast north of the island of Ischia (Fig. 5) has revealed a fault system with at least one WNW-ESE trending normal fault with a strike-slip component (Bruno *et al.*, 2000) but no major strike-slip fault crossing the whole domain, as also suggested by Conti *et al.* (2017). This region thus does not show any prominent strike-slip fault but rather a series of short steep normal and strike-slip faults oriented obliquely on the expected strike of the transfer zone.

Further south, a series of N-S trending normal faults dissect the crust until the deep Vavilov basin where recent seismic investigation have revealed the presence of exhumed mantle instead of the expected oceanic crust (Prada *et al.*, 2014, 2016, 2018) (Fig. 5). A similar situation is probable also for the more recent Marsili basin further to the SE. From the coast of Sardinia toward the east, a gradient of crustal thickness is observed with a set of N-S-trending normal faults delimitating crustal blocks and shaping a wide margin (Sartori *et al.*, 2004; Lymer *et al.*, 2016). The distribution of the Messinian salt deposits and its relation with block formation show that rifting lasted until the Messinian on this margin, including the Cornaglia Terrace and part of the Vavilov basin (Lymer *et al.*, 2016; Haq *et al.*, 2020) while the Marsili basin appears more recent without Messinian deposits (Fig. 5).

Sicily displays a stack of nappes extending eastward the Maghrebian Belt (Roure *et al.*, 1990; Catalano *et al.*, 2013; Gasparo Morticelli *et al.*, 2015). Paleomagnetic studies along transects of the nappe stack have revealed a gradient of clockwise rotation from south to north (Channell *et al.*, 1990). The origin of these rotations is debated. Channell *et al.* (1990) and Oldow *et al.* (1990) proposed a model of progressive southward thrusting during a regional clockwise rotation leading to the observed gradient. Giunta *et al.* (2000) and Guarnieri (2004) later suggested instead the role of a series of right-lateral strike-slip faults oblique to the margin and accommodating the clockwise rotation. A detailed study of a N-S transect (Speranza *et al.*, 2018) however recently showed that the rotations associated with the strike-slip faults fade away from the faults within a few hundred meters and cannot explain the general gradient of rotation, thus reemphasizing the model initially proposed by Channell *et al.* (1990).

The eastern margin of Tyrrhenian Sea shows some oblique rifting with normal faults oblique on the strike of the margin (Fig. 5). Milia *et al.* (2018) and Conti *et al.* (2017) show the distribution of these faults offshore and their progressive formation during the opening of the Vavilov and Marsili Basins. An association of normal and left-lateral strike-slip faults and normal faults is reported but normal faults predominate within what has to be a wide left-lateral shear zone (faults with orange color in Fig. 5). This shear zone ends in the south within the Diamante-Enotrio-Ovidio intrusive complex with aligned intrusions that may be set on top of a strike-slip system with an extensional component and interpreted as the effect of a step-fault at the surface by De Ritis *et al.* (2019). This link between transfer faults and volcanism is reminiscent of the situation described above along the Catalan Transfer Zone and was shown also for smaller-scale transfer faults along the Italian Tyrrhenian margin by Acocella and Funiciello (2006).

4 Transfer zones in the Alboran region

The westward displacement of the Alboran Domain (Figs. 6–8) from the Burdigalian to about 8 Ma is accommodated very differently on the northern and southern margins of the Alboran Sea and Algerian Basin. The southern transfer zone is characterized by a series of en-échelon left-lateral strike-slip faults while the northern margin, on the Betic side, shows mostly large-scale low-angle detachments and stretching-parallel a-type metamorphic domes. The leading edge of the westward-moving Alboran block is thrusted over the Iberian and African continental margins during the same period.

4.1 Rif-Tell and en-échelon-strike-slip faults

The Rif and Tell form an elongated stripe of exhumed basement (the internal zones) overthrusting external thrust sheets with the Flysch Units in between (Figs. 6 and 7). The observation of Neogene sedimentary basins shows a migration of deformation from east to west, starting in the Late Burdigalian in Algeria, reaching the eastern Rif in the Late Tortonian and the Rharb basin in the Pliocene (Leprêtre *et al.*, 2018). A coeval migration of magmatism is observed along the same trend, with a transition in time from calc-alkaline to alkaline affinity, suggesting the development of a slab tear (Maury *et al.*, 2000). The left-lateral strike-slip component of this movement is accommodated by several en-échelon strike-slip faults, such as the SW-NE striking Jebha and Nekor faults in Morocco or several faults with the same orientation and behavior offshore Algeria between Oran and Algiers, acting from Langhian to Tortonian. In the southern Alboran Sea the Yusuf fault and Alboran ridge, striking NW-SE and SW-NE respectively, are seemingly inherited structures which acted as important strike-slip structures (Martinez-Garcia *et al.*, 2013, 2017). The present-day configuration of the faults in the Alboran Sea is compatible with a N-S shortening with a conjugate set of strike-slip faults (Le Pourhiet *et al.*, 2014). Recent offshore investigations deciphered the detailed geometry and relative timing of this recent set of faults crossing the Alboran Sea from south to north. A progressive localization of N-S left-lateral strike-slip system with perpendicular thrust faults has occurred from the early Pliocene to the present, reworking an older set of faults parallel to the Carboneras and Jebha faults (Martinez-Garcia *et al.*, 2013, 2017; d'Acremont *et al.*, 2020; Lafosse *et al.*, 2020). The existence of localized spreading centers in the oceanic domain of the Algerian basin with transform faults with a similar orientation has been proposed by Medaouri *et al.* (2014). This deformation appears sealed by the Late Miocene and reworked by a N-S shortening in Morocco (Leprêtre *et al.*, 2018).

4.2 Betics and a-type domes

In the Internal Zones of the Betic Cordillera (Fig. 6), a major kinematic change occurs at around 20 Ma. Before that period, stretching lineations associated with extensional low-angle shear zones are mostly N-S or NNE-SSW and kinematic indicators showing a top-to-the north sense of shear (Crespo Blanc *et al.*, 1994; Crespo Blanc, 1995; Balanya *et al.*, 1997; Negro *et al.*, 2005; Jolivet *et al.*, 2006, 2008; Augier *et al.*, 2013; Platt *et al.*, 2013; Williams and Platt, 2018). This early deformation is observed in the entire outcropping domain of the Alpujarride complex, separated from the overlying Malaguides by the Malaguide-Alpujarride Contact (MAC),

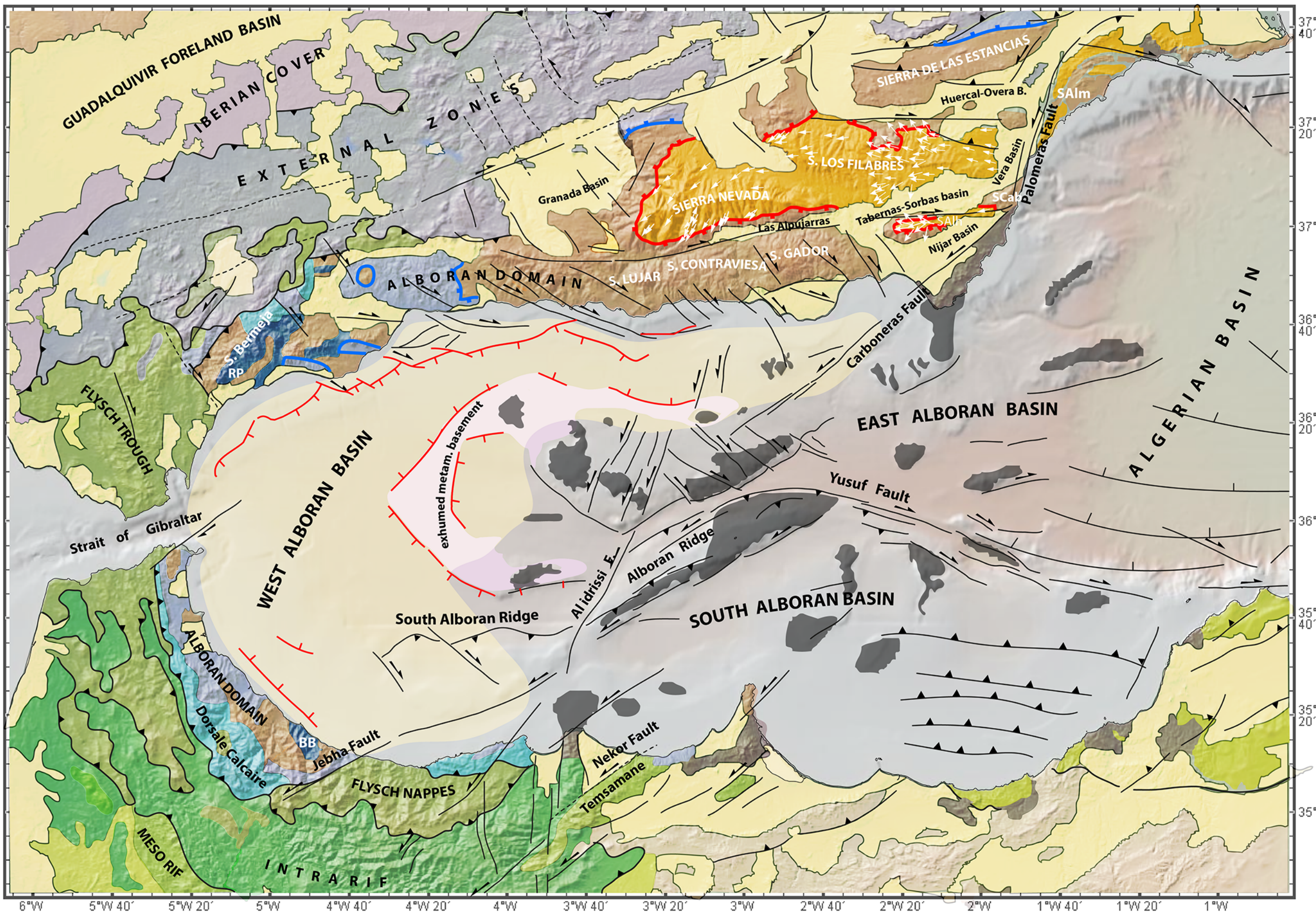

Fig. 6. Tectonic map of the Alboran region (Comas *et al.*, 1999; Augier *et al.*, 2005a, 2005b; Chalouan *et al.*, 2008; Medaouri *et al.*, 2014; Crespo-Blanc *et al.*, 2016; Do Couto *et al.*, 2015; Martinez-Garcia *et al.*, 2017; d'Acremont *et al.*, 2020; Lafosse *et al.*, 2020). Bathymetry and topography from GeoMapApp (Ryan *et al.*, 2009). RP: Ronda peridotite massif, BB: Beni Bousera peridotite massif. The thick blue line represents the Malaguide-Alpujarride Contact Detachment and the thick red line the Filabres and Mecina Detachments between the Alpujarride and Nevado-Filabride complexes. Thin red lines are the offshore syn-rift normal faults.

a major top-to-the north detachment (Lonergan and Platt, 1995). After 20 Ma, two sequentially developed W-directed extensional detachments (*i.e.* the Filabres and the Mecina detachments) exhumed the deepest tectonic stack of the Betics, the Nevado-Filabride Complex (Jabaloy *et al.*, 1993; Martínez-Martínez *et al.*, 1997, 2002; Augier *et al.*, 2005a, 2005b). The main direction of stretching then becomes E-W to ENE-WSW with a top-to-the west sense of shear. The domal geometry of the Sierra-Nevada/Sierra de los Filabres and the Sierra Alhamilla metamorphic core complexes (Figs. 6 and 8) was amplified after the Late Tortonian by large-scale crustal-scale folds with axes parallel to the E-W original dome axes (Sanz de Galdeano and Vera, 1992; Comas *et al.*, 1999; Iribarren *et al.*, 2009; Do Couto *et al.*, 2015; Janowski *et al.*, 2017). The pattern of stretching lineations within the domes shows that the domal shape already existed before this late Tortonian N-S contractional episode as shown by the divergence of stretching lineations that trend E-W in the core of the domes and diverges toward the NW and SE toward their margins (Augier *et al.*, 2005a). During the exhumation of domes and before the N-S shortening episode, intramountain extensional basins started to developed on either sides with oblique stretching directions suggesting a component of gravitational sliding on the detachment (Orozco *et al.*, 1997; Augier *et al.*, 2013). This geometry confers to these domes the characteristics of a-type domes (Jolivet *et al.*, 2004; Le Pourhiet *et al.*, 2012), elongated parallel to the main direction of the post-20 Ma stretching. In between these domes, a limited number of E-W striking dextral brittle strike-slip systems develop such as in the Alpujarras corridor (Martínez-Martínez *et al.*, 2006) or along the contact between the Internal and External Zones (Frasca *et al.*, 2016), although some of these steeply-dipping fault planes correspond to tilted low-angle detachments. The main displacement is thus accommodated on low-angle shear zones, which contrasts with the opposite side of the Alboran domain and Algerian Basin where en-échelon strike-slip accommodate the displacement.

The northern and southern transfer zones framing the Alboran Sea between 20 and 8 Ma thus show a different behavior with a-type domes in the north and en-échelon strike-slip faults in the south. However, it should be noted here that the Betics show an evolution through time from ductile to brittle, the ductile behavior being associated with the formation and exhumation of the a-type domes and the brittle behavior

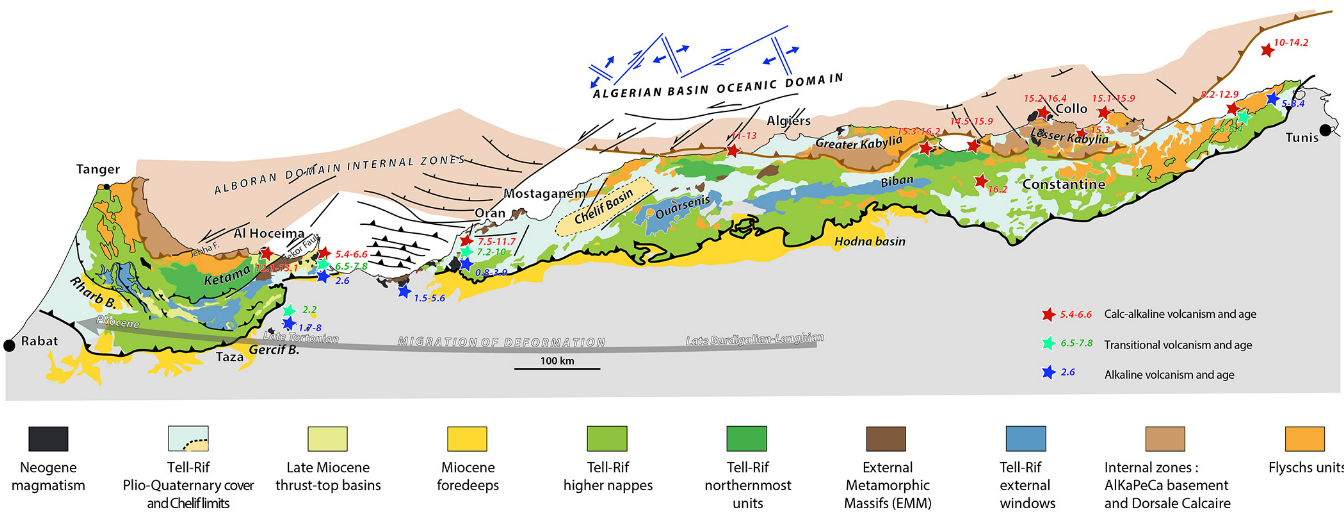

Fig. 7. Tectonic map of the northern margin of Africa, compiled from Leprêtre *et al.* (2018) and Medaouri *et al.* (2014).

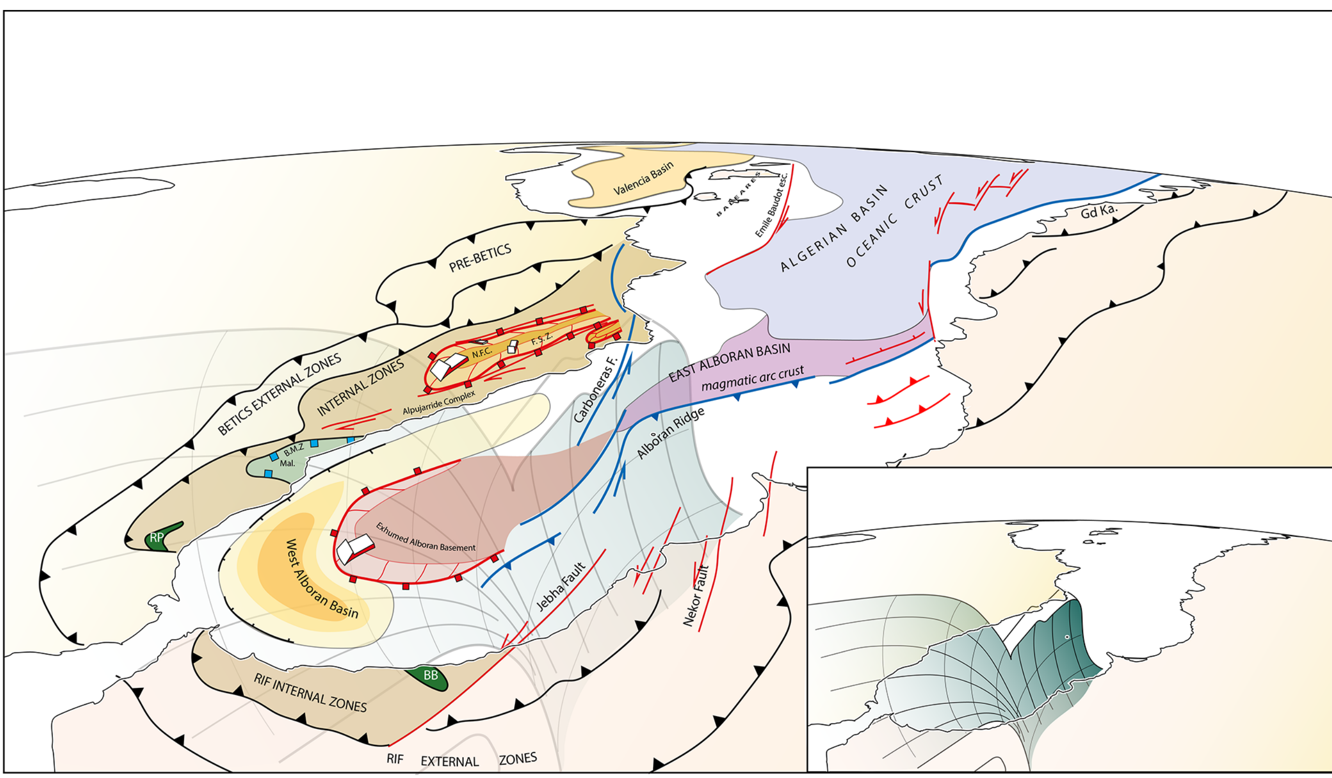

Fig. 8. Oblique 3-D view of the Alboran region and slab geometry after Bezada *et al.* (2013) and Villaseñor *et al.* (2015).

involving E-W strike-slip faults and narrow corridors. The low-angle detachment exhuming the Sierra Nevada-Sierra de Los Filabres MCC was active until it reaches the brittle field as shown by low-temperature thermochronology (Johnson *et al.*, 1997). A similar behavior is recorded in the Aegean region.

5 Transfer zones in the Aegean Sea

Two wide transfer zones accommodate (1) the differential 50° clockwise rotation between the western branch of the Hellenides and Anatolia in the eastern Aegean above the main slab tear and (2) the propagating junction between the North Anatolian Fault and North Aegean Trough toward the nascent slab tear documented below the Peloponnese (Figs. 9 and 11). These two transfer zones are at radically different stages of their evolution.

5.1 West Anatolian Transfer Zone

The Eastern Aegean Islands, the Dodecanese and the Menderes Massif form a wide zone of transfer, named the West Anatolian Transfer Zone (WATZ) by Gessner *et al.* (2013).

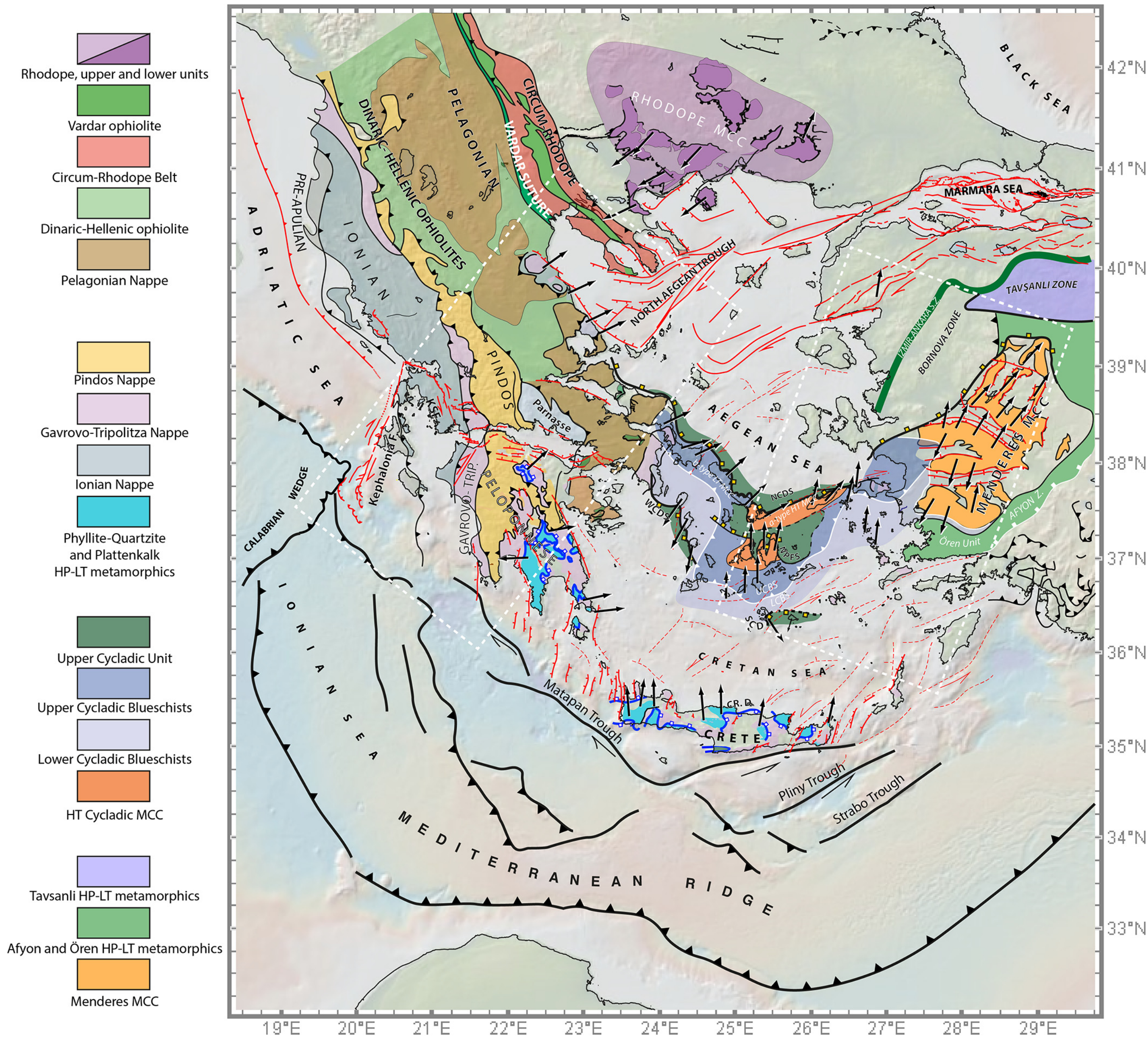

Fig. 9. Tectonic map of the Aegean region (Gessner *et al.*, 2001; Le Pichon *et al.*, 2002; Chamot-Rooke *et al.*, 2005; Brun and Sokoutis, 2007, Brun and Sokoutis, 2018; Jolivet and Brun, 2010; Iglseder *et al.*, 2011; Burg, 2012; Grasemann *et al.*, 2012; van Hinsbergen and Schmid, 2012; Rabillard *et al.*, 2015; Grasemann *et al.*, 2017; Pérouse *et al.*, 2017; Schneider *et al.*, 2018; Roche *et al.*, 2019). White dotted frames represent the Central Hellenic Shear Zone (CHSZ) and the West Anatolian Shear Zone (WASZ). Red lines represent faults related to the recent strike-slip and extensional tectonics associated with the propagation of the North Anatolian Fault.

Located above the main slab tear deduced from tomographic models of the Eastern Mediterranean (de Boorder *et al.*, 1998; Biryol *et al.*, 2011; Salaün *et al.*, 2012; Govers and Fichtner, 2016), its existence was first proposed by Ring *et al.* (1999) to accommodate the larger extension in the Aegean compared with the Menderes Massif (Figs. 10 and 11). It includes the Izmir-Balıkesir Transfer Zone (IBTZ), bounding the Menderes Massif to the NW, with a polyphase evolution and reworked recently as a dextral brittle shear zone (Sözbilir *et al.*, 2011; Uzel *et al.*, 2012, 2019). Uzel *et al.* (2019) show a major break in the magmatic evolution of this region with a gap in magma production between 16 and 14 Ma and a transition from calc-alkaline to alkaline product at the same period, which they relate to the formation of the tear in the slab underneath. These recent findings confirm and precise earlier propositions by Dilek *et al.* (Dilek and Altunkaynak, 2009; Dilek and Sandvol, 2009) of the important role played by the same tear on the magmatic evolution of Western Anatolia and the detailed reconstructions and 3-D numerical models of Menant *et al.* (2016a). The WATZ is wider than the IBTZ and encompasses the eastern Aegean region and the entire Menderes Massif. It was recently reassessed by Gessner *et al.* (2013), Jolivet *et al.* (2015b), Ring *et al.* (2017) and Roche *et al.* (2019).

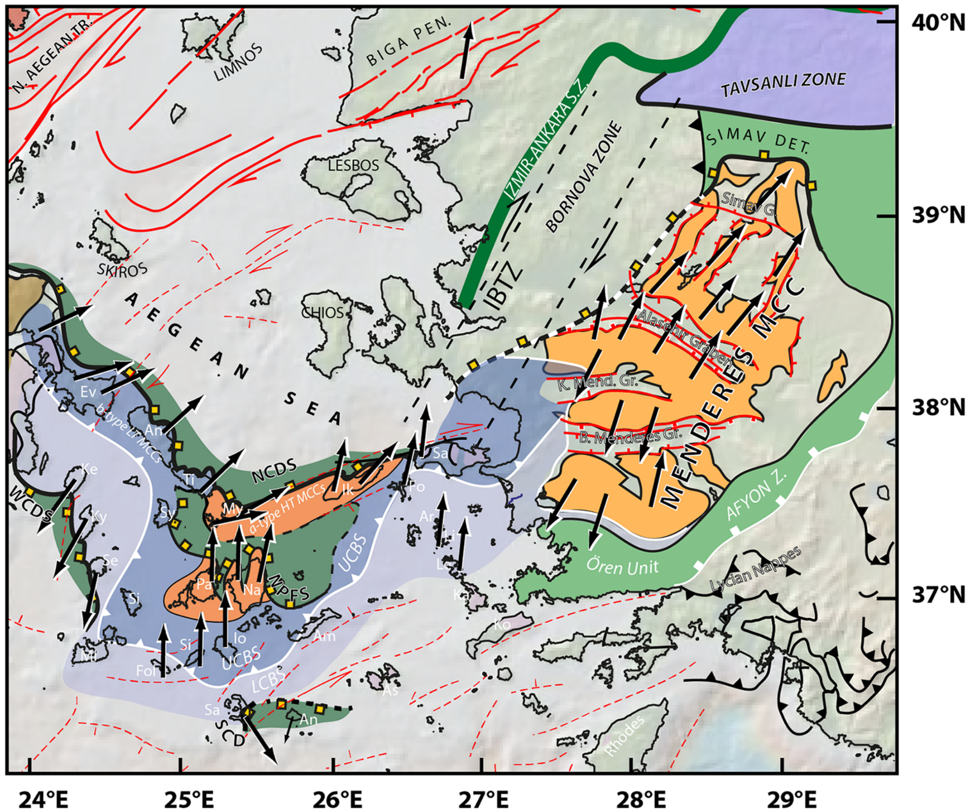

Fig. 10. Detail of Figure 9 focused on the Cyclades and the Menderes Massif. Am: Amorgos; An: Anafi; An: Andros; Ar: Arki; As: Astipalaea; Ev: Evvia; Fo: Fourni; Fol: Folegandros; IBTZ: Izmir-Balikesir Tranfer Zone; Ik: Ikaria; Io: Ios; Ka: Kalimnos; Ke: Kea; Ko: Kos; Ky: Kythnos; Le: Leros; Li: Lipsi; My: Mykonos; Na: Naxos; NCDS: North Cycladic Detachment System; NPFS: Naxos-Paros fault System; Pa: Paros; Sa: Samos; Sa: Santorini; SCD: South Cycladic Detachment; Se: Serifos; Si: Sikonos; Sy: Syros; Ti: Tinos; UCBS: Upper Cycladic Blueschists; WCDS: West Cycladic Detachment System

Ring *et al.* (2017) document brittle deformation within the Eastern Aegean Islands and the Dodecanese. They show a dominant NNE-SSW extension since the Early Miocene with a minor component of perpendicular contraction, probably not contemporaneous everywhere. In Samos Island, the main direction of extension is more E-W and Ring *et al.* (2017) relate it to the formation of transtensional left-lateral corridor in the Early and Middle Miocene. No large-scale localized strike-slip fault is described. Roche *et al.* (2019) have focused their observations on ductile deformation instead and the exhumation of metamorphic units. They also conclude to N-S to NNE-SSW extension accommodated by low-angle north-dipping shear zones in the islands of Leros, Lipsi, Arki and Fourni. This main direction of extension is similar to that of the Menderes Massif to the east and the Cyclades to the west. The absence of major strike-slip faults show that the transfer zone is characterized by a gradient of finite extension accommodated by low-angle shear zones and detachments. The brittle evolution of the Cyclades MCC (Mehl *et al.*, 2005, 2007; Brichau *et al.*, 2006, 2008; Lacombe *et al.*, 2013; Menant *et al.*, 2013; Ring *et al.*, 2017) shows a continuum of extension along low-angle normal faults until superficial levels of the crust from Late Oligocene to Late Miocene. The most recent evolution also involves steeper faults, including strike-slip faults and normal faults, or even locally reverse faults during short periods (Ring *et al.*, 1999; Menant *et al.*, 2013) but no connection of strike-slip faults on long distances and thus no large displacements along steeply-dipping strike-slip systems. This evolution is partly due to a change in the stress regime around 9 Ma toward a more compressional regime during a short period, possibly due to the westward extrusion of the Anatolian plate and the North Anatolian Fault (Menant *et al.*, 2013). The deformation in the upper crust during the activity of the low-angle detachments is described mostly based on small-scale fault geometry and kinematics (Mehl *et al.*, 2005, 2007; Lacombe *et al.*, 2013) and the big picture is often lacking. The example of the Miocene basins of Samos and their bounding faults show this complexity (Ring *et al.*, 1999). The example of Mykonos however shows that the detachment remained active late until the deposition of a supra-detachment basin (Menant *et al.*, 2013).

As suggested by Jolivet *et al.* (2015b), the effect of the slab tear is felt all the way to the center of the Cyclades. The metamorphic core complexes of Ikaria, Mykonos and Naxos were exhumed below low-angle detachments (NCDS and NPFS) in the Early and Middle Miocene with N-S or NE-SW direction of extension and top-north or top-NE sense of shear in high-temperature conditions associated with partial melting and intrusion of leucogranites. These H-*T* domes are elongated parallel to the main direction of extension and served as examples to define a-type domes (Jolivet *et al.*, 2004), as opposed to the b-type domes of the western Aegean. As shown

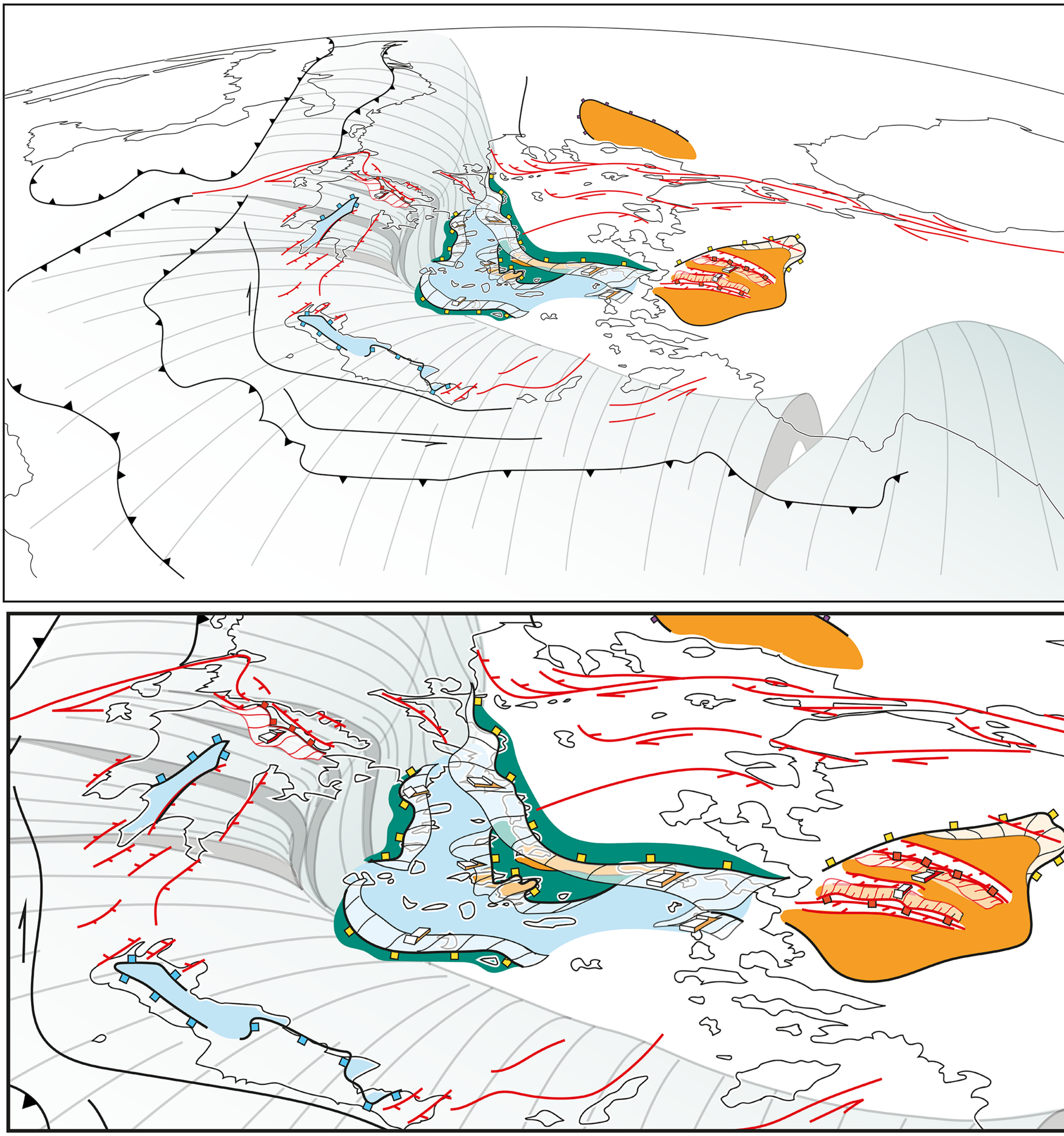

Fig. 11. 3-D view of the Aegean region and the geometry of the slab underneath. The slab is shown in light gray and all other structures are in the crust at the top of the model.

by Le Pourhiet *et al.* (2012) through 3-D numerical modelling, a-type domes are diagnostic of a component of strike-slip motion at the boundaries of the deforming zone and Jolivet *et al.* (2015b), Menant *et al.* (2016b) and Roche *et al.* (2018b) related these domes and the propagation of the Miocene Aegean granites from 16 to 8 Ma to the formation of the tear and associated asthenospheric flow. Further west, MCCs are exhumed below NE-dipping (NCDS) and SW-dipping (WCDS) detachments. These domes are mostly elongated perpendicular to the main stretching direction in Tinos, Andros, Kea or Kythnos. Recent findings also document the presence of a S-dipping detachment on the island of Santorini (Schneider *et al.*, 2018). The transition in space from the b-type domes of Andros-Tinos to the a-type domes of Naxos and Ikaria is associated with a difference in the direction of the stretching lineation, notably on Paros island. This difference

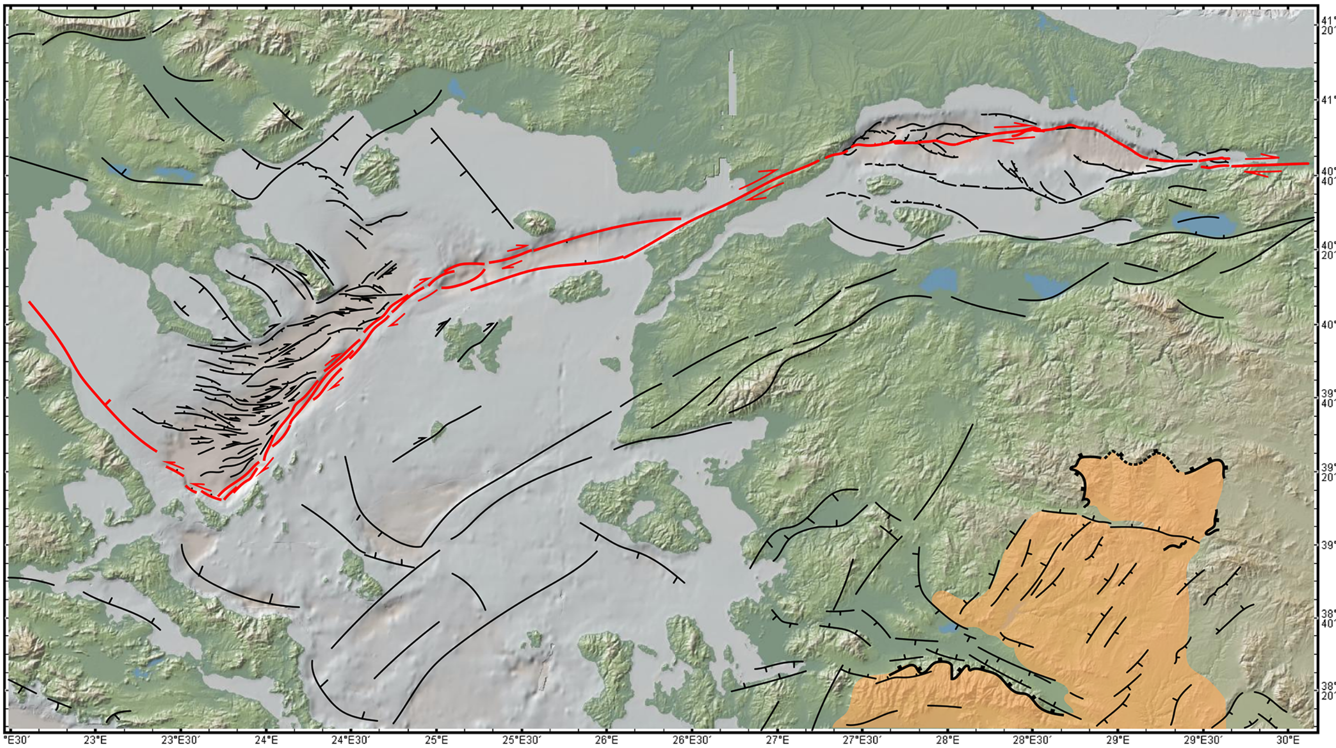

Fig. 12. Recent and active faults in the northern Aegean and the Marmara Sea (Le Pichon *et al.*, 2001, 2003; Armijo *et al.*, 2004). The red faults are the most recent ones.

has been interpreted as reflecting the activity of a dextral strike-slip system, the Mid-Cycladic Lineament (Gautier and Brun, 1994a, 1994b; Walcott and White, 1998; Philippon *et al.*, 2014) separating two rigid blocks during extension. The propagation of a deep transtensional fault and the development of a-type and b-type domes in the crust above proposed as the favored setup for the Cycladic example in the numerical models of Le Pourhiet *et al.* (2012) can however explain this difference in the orientation of the stretching direction without the necessity of a localized strike-slip fault and two rigid blocks (see below the discussion of 3-D numerical models).

5.2 Central Hellenic Shear Zone and North Anatolian Fault

The divergence of the axes of the two lines of Miocene b-type domes, Evvia, Andros, Tinos in the northern Cyclades and Kea, Kythnos, Sifnos, Serifos in the western Cyclades shows the gradient of extension from continental Greece to the Aegean (Jolivet *et al.*, 1994) outside the zone affected by the slab tear below the eastern Aegean. The geometry of active extension is this region is reminiscent of the pattern seen in the Cyclades with the asymmetrical development of the Corinth Rift above low-angle north-dipping shear zones and detachment (Sorel, 2000; Flotté and Sorel, 2001; Flotté *et al.*, 2005; Jolivet *et al.*, 2010) but its most recent evolution shows a localization of deformation along a few large-scale steeply-dipping normal faults, that pertains to the formation of the second tear fault below the Peloponnese and the development of the Central Hellenic Shear Zone (Royden and Papanikolaou, 2011).

The connection between the North Anatolian Fault and the Hellenic Trench was analyzed as early as 1972 in seminal papers by McKenzie (1972, 1978) and drawn at this stage as a straight line connecting the two plate boundaries. Later, the role of rotating parallel normal faults distributing the strain across a wide zone was recognized (Jackson and McKenzie, 1983; McKenzie and Jackson, 1986). The rotating broken-slats model of Taymaz *et al.* (1991) was proposed to explain the geometry and the rotation of normal faults in opposite sense on the Greek and Turkish sides of the Aegean domain. Detailed tomographic models at the transition of the Hellenic subduction east of the Kephalonia Fault and continental collision further to the northwest recently suggested that the slab is there divided in two parts by a nascent tear fault where the Aegean side retreats faster (Suckale *et al.*, 2009; Sachpazi *et al.*, 2016). Sachpazi *et al.* (2016) more precisely describe a stepwise dilaceration of the slab along a set of parallel faults underneath the Peloponnese.

Papanikolaou and Royden (2007) and Royden and Papanikolaou (2011) then proposed that the portion of lithosphere located above this nascent tear corresponds to a wide shear zone, the Central Hellenic Shear Zone (CHSZ) (#2 on Figs. 2 and 9), including the Evvia and Corinth Rifts and the normal faults cutting the Peloponnese, making the connection between the North Anatolian Fault propagating toward the Hellenic Trenches. No significant strike-slip faults are recognized in this zone of distributed extension. Two active pure dextral strike-slip faults are observed southwest of the Peloponnese, the offshore Kephalonia Fault and one parallel fault in northwest Peloponnese complete the junction with the trench (Pérouse *et al.*, 2017; Haddad *et al.*, 2020).

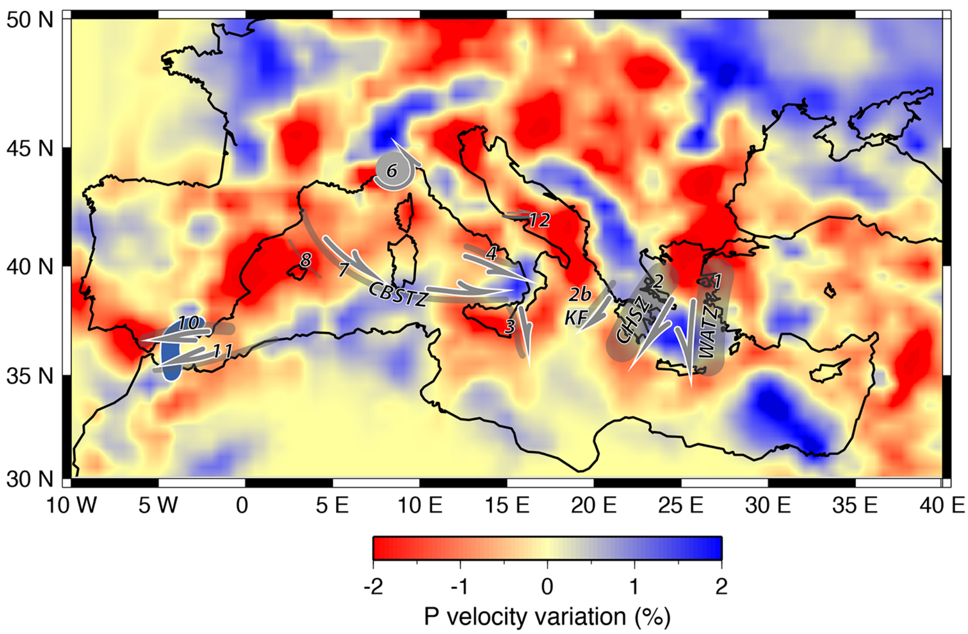

Fig. 13. Localisation of the main discussed transfer zones on top of a P-wave tomographic model. The model is from Piromallo and Morelli (2003) and shows the average V_P perturbation in the upper mantle (vertical average between 100 and 250 km), after Jolivet *et al.* (2009). The blue shape near Gibraltar is the VP anomaly due to the Gibraltar slab after Villaseñor *et al.* (2015).

The initiation timing of the CHSZ is not precisely known. Extension in the Gulf of Corinth dates back to at least 4–5 Ma and the early deformation was distributed across a wide zone of the southern margin of the present Gulf, controlled by a north-dipping detachment (Sorel, 2000; Flotté and Sorel, 2001; Flotté *et al.*, 2005; Ford *et al.*, 2007; Rohais *et al.*, 2007; Backert *et al.*, 2010; Jolivet *et al.*, 2010; Rohais and Moretti, 2017). It then progressively localized and finally activated the main faults making the steep topographic gradients of the southern shore, along the Xylocastro and Helike Faults (Armijo *et al.*, 1996; Jolivet *et al.*, 2010). This transition is abruptly recorded in the evolution of the giant Gilbert-type deltas decorating the tilted blocks of the southern margin of the rift. They were uplifted some 600 kyrs ago and are now replaced by the active deltas (Ford *et al.*, 2007; Rohais *et al.*, 2007; Backert *et al.*, 2010). This is in line with the timing of propagation of the North Anatolian fault proposed by Armijo *et al.* (1999) with the NAF reaching the Dardanelles Strait some 6 Ma ago and then the coast of continental Greece a few Ma ago. One can postulate that this transition and the localization of deformation record the initiation of the tear and the initiation of the accommodation zone in the crust. In that case, the preceding period would belong more to a Cycladic-type evolution leading to the formation of MCCs (Jolivet *et al.*, 2010). The development of alkaline magmatism during the Pliocene and Quaternary near the southwestern termination of the North Aegean Trough in Psathoura and Euboecos (Pe-Piper and Piper, 2006, 2007) is also in line with this timing if one relates this magmatic production to the slab tear, but this recent magmatic episode could also be linked with the propagation of the NAF strike-slip system in the Aegean domain, which could itself be a consequence of slab tearing (Sternai *et al.*, 2014). If this timing holds, the development of the Central Hellenic Shear Zone would then start with the formation of grabens in a Cycladic style with low-angle normal faults and shear zones exhuming metamorphic core complexes (b-type) and then the progressive localization of a wide transfer zone associated with the development of a tear in the slab underneath.

The propagation and progressive localization of the North Anatolian Fault has been described as a consequence of the extrusion of the Anatolian block due to the Arabia-Eurasia collision (McKenzie, 1972, 1978; Armijo *et al.*, 1999). But the increasing velocity of extension toward the trench and recent approaches with 3-D numerical modelling suggest instead that the NAF is also a consequence of slab retreat and slab tearing (Faccenna *et al.*, 2006; Jolivet *et al.*, 2013; Capitanio, 2014; Sternai *et al.*, 2014). Instead of a simple push from the SE, Anatolia would be partly dragged by the southward retreat of the Hellenic slab between two step-faults. This would then make the southwestern extension of the NAF in the North Aegean Trough and in the CHSZ the equivalent of the transfer faults accommodating different rates of extension above slab tears described in this paper. The recent evolution of the fault trace (Fig. 12) shows that the localization is still in progress in Quaternary times as the fault is observed with recent aligned scarps within the wider Marmara Sea pull-apart basin (Le Pichon *et al.*, 2001, 2003; Armijo *et al.*, 2004). In this case, a diffuse shear zone or fault zone has evolved into a localized fault following the small circles about the Anatolia/Eurasia Eulerian pole, progressively creating a new plate boundary.

6 Discussion

This summary of the distinctive features of the studied transfer zones allows sorting between real transfer zones related to slab tears and those whose existence is doubtful, the latter being shown with dotted lines in Figure 2. All other transfer zones observed in the back-arc domain can be

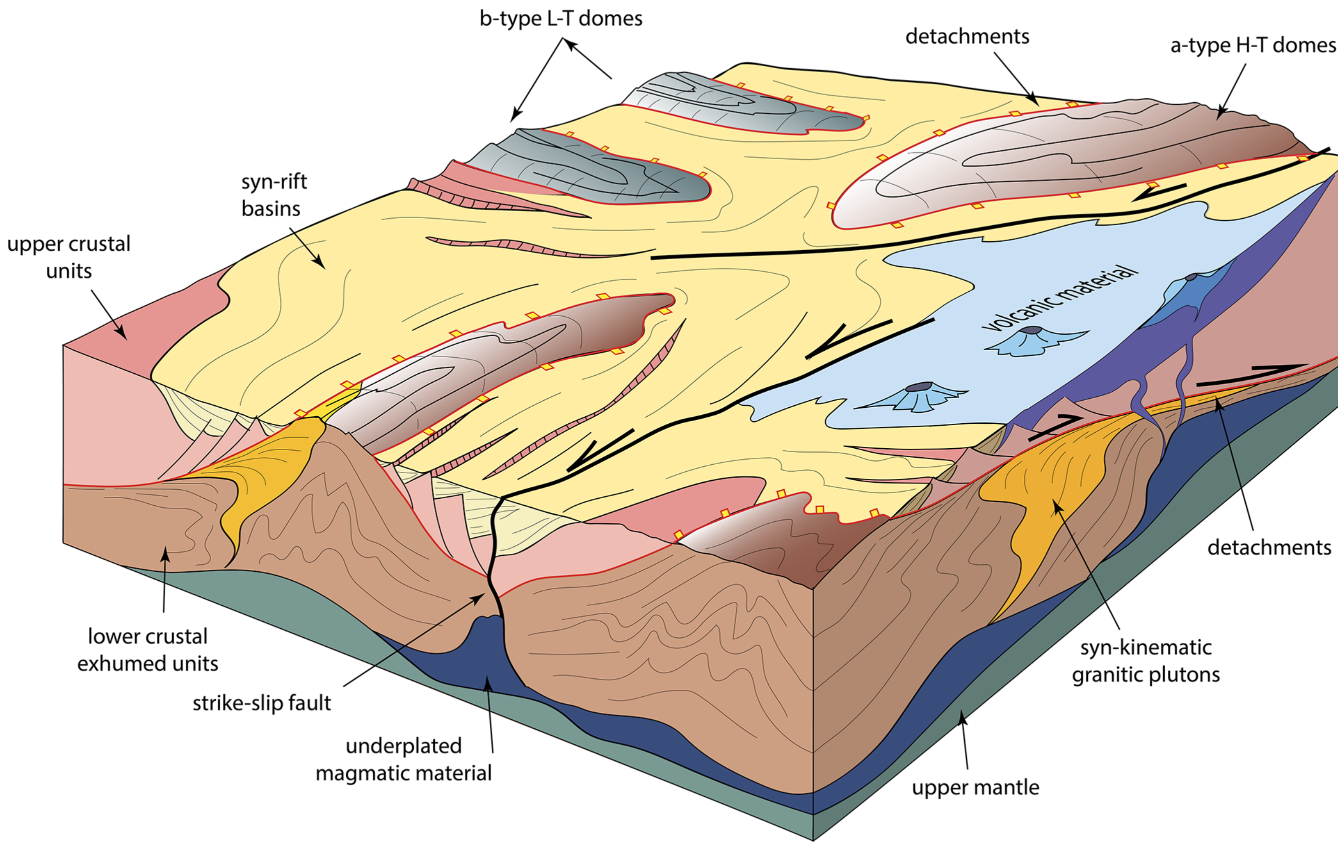

Fig. 14. Summary of the variety of structures found within transfer zones.

associated with a tear in the slab underneath. Figure 13 shows these transfer zones on top of a V_P seismic tomographic model after Piromallo and Morelli (2003) together with the shape of the Gibraltar slab after Villaseñor *et al.* (2015). This map shows that the main transfer zones are above the limits of slab pieces at depth. TZ#1 and #2-2b correspond to the two tears bounding the Hellenic slab on the eastern and western sides. TZ#6 is located above the large zone where the Alpine and Apennine slab interact. TZ#4 and #7 correspond to the two tears that limit the Ionian slab below the Tyrrhenian Sea on its northern and southern sides. A similar situation can be deduced for TZ#10 and #11 on either side of the Gibraltar torn slab. The longest of these transfer zones is the CBTSZ (#7), which results from the progressive tearing of the future Apennine slab and which separated the future Apennine subduction from the Algerian subduction. All these transfer zones have distinctive characteristics, they are more or less wide, they have brought to the surface deep crustal tectonic units or, on the opposite, show mostly brittle structures, but they also show some common features that are due to their position above a slab tear in a back-arc region.

This review then brings to light some first-order observations. One of the first points is the dissemblance of the style of transfer faults on either side of the back-arc basins. The Betics shows main low-angle normal faults while the North African margin shows mostly en-échelon strike-slip faults. The West Anatolia Transfer Zone also shows mostly low-angle normal faults and MCCs while the Central Hellenic Shear Zone is characterized mainly by rotating steep normal faults. These differences can be due to different stages of evolution in the case of the Aegean or different distances with respect to the main slab tear. These different behaviors of the crust above slab tears should be further investigated. Figure 14 shows a synthetic 3D diagram summarizing the main features observed associated with transfer faults in the back-arc regions of the Mediterranean.

6.1 Low-angle extensional shear zones is the rule in the middle and lower crusts, few significant crustal-scale strike-slip faults

A first-order observation is the frequent lack of true strike-slip faults of a significant scale. Short and discontinuous strike-slip faults are found in the trench area where they limit laterally the accretionary wedges of Calabria (Malta escarpment) or the Mediterranean Ridge (Kephalonia fault), or in the distant back-arc region with the example of the North Aegean Trough. Another exception is the north African margin, where the westward displacement of the Alboran block during the early and middle Miocene is accommodated by en-échelon strike-slip faults and intervening thrust faults. No detailed information is available on the deep expression of this deformation, whether the strike-slip faults affect the entire crust or only the upper crust, but the emplacement of early Miocene granite associated with strike-slip faulting in the Rif may suggest that the whole crust is affected (Rossetti *et al.*, 2013).

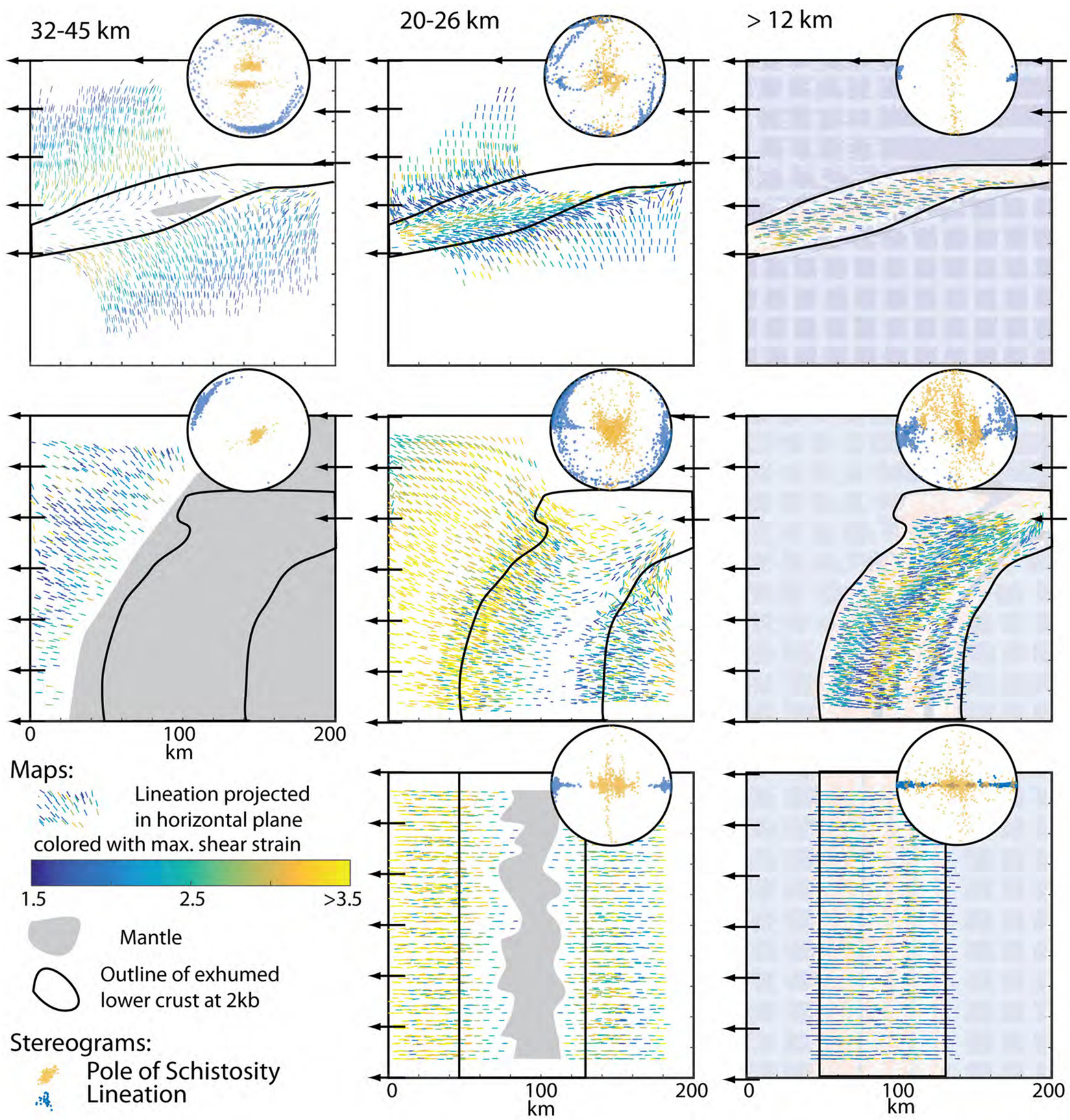

Fig. 15. Lineation maps at different depths extracted from the 3-D numerical models of Le Pourhiet *et al.* (2012) in three different setups. Upper: extensional step-over; middle: transtensional fault propagator; lower: cylindrical extension.

On the northern side of the migrating Alboran block instead, the relative motion is mostly accommodated by low-angle shear zones and detachments, forming crustal-scale a-type metamorphic core complexes such as the Sierra Nevada or Sierra Alhamilla. A similar geometry is observed in the West Anatolian Transfer Zone with mostly low-angle normal faults and detachments exhuming high-temperature a-type metamorphic core complexes such as Naxos or Ikaria. Similar domes are found at depth in the lower crust along the Catalan Transfer fault or the North Baleares Fracture zone, associated with the emplacement of a large volcanic province at the surface during rifting and underplating of mafic material at depth. In this case, the superposition of lower and upper crustal deformation has been preserved and can be observed on seismic profiles (Fig. 4). In the case of the Aegean or the Betics, the exhumation of mid and lower crustal structures has partly erased the record of upper crustal deformation. The image provided by the North Baleares Fracture Zone may be partly transposed to other contexts with basins controlled by transtension faults in the upper crust and low-angle shear zones in the middle crust, the lower crust and the upper mantle. One specificity of the Betics and the Aegean is however that the low-angle shear zones continue to be active until shallow portions of the crust during exhumation. The transposition of the mechanical stratification observed across the North Baleares Transfer Zone is thus probably not totally correct in the case of the Aegean and the Betics. It nevertheless remains that the upper crust and the lower crust behaved differently in all these examples with more numerous steep normal faults controlling basins and short, disconnected strike-slip faults in the upper crust compared with the low-angle shear zones of the middle and lower crusts.

The geometry of lower crustal domes exhumed within the transfer zones in the Betics and the Aegean are compatible with

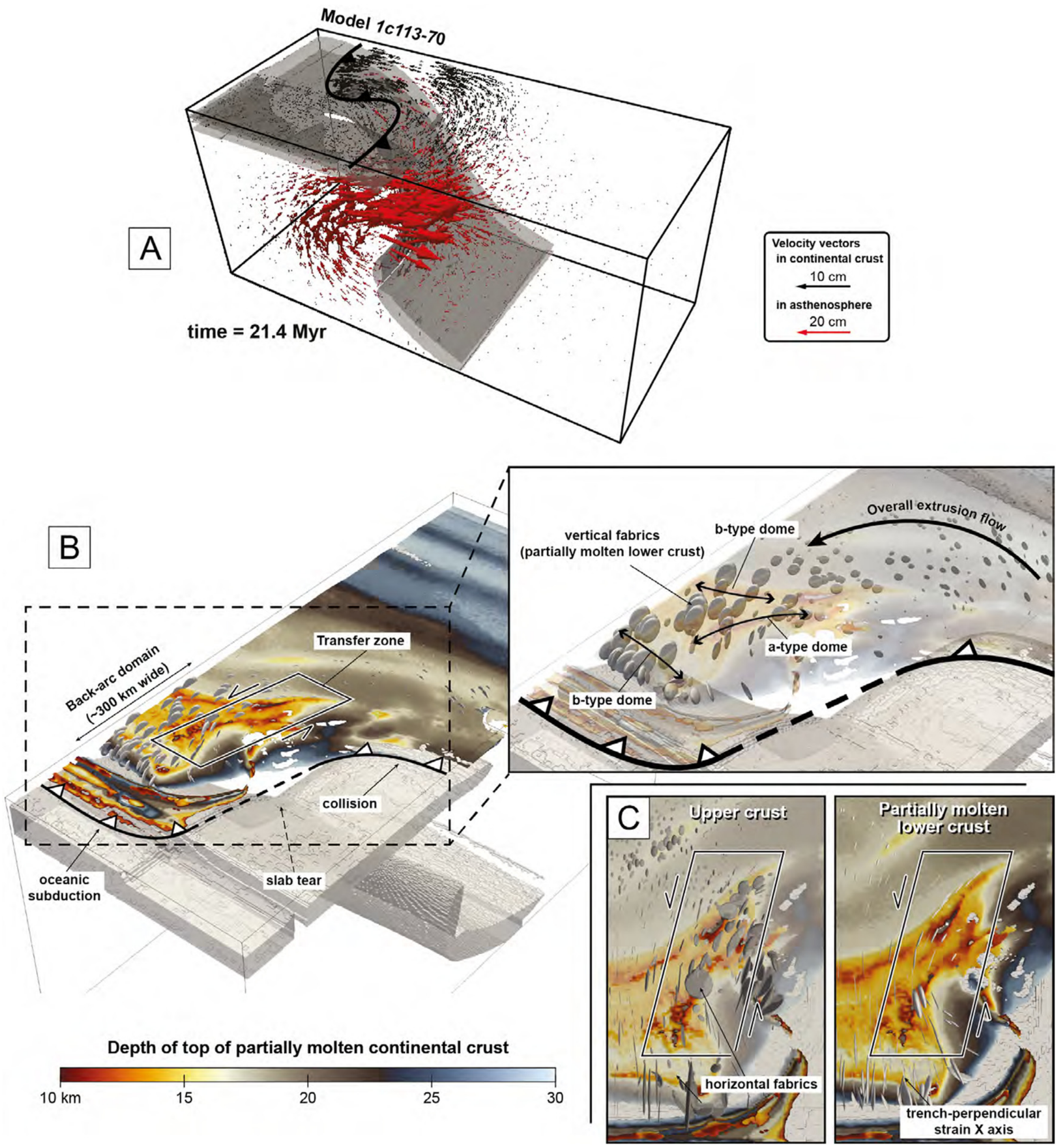

Fig. 16. Lithospheric-scale 3-D numerical model of Menant *et al.* (2016a, 2016b). A: mantle velocity field (red arrows), crustal velocity field (black arrows). B: 3-D view from above showing the depth of the top of the lower molten crust in the back-arc region and the finite strain ellipsoids in the lower crust and the position of a-type and b-type domes. C: map view of details of the model focused on the transfer zone above the slab tear showing in addition finite strain ellipsoids in the upper crust.

a component of strike-slip at the boundaries of the deforming system (Le Pourhiet *et al.*, 2012). The most striking example is the case of the Betics with the large Sierra Nevada-Sierra de Los Filabres and the smaller Sierra Alhamilla a-type domes. In this case the pattern of stretching lineations and sense of shear is similar to the pure a-type dome setup of the numerical model. The case of the Aegean where a-type domes connect laterally with b-type dome is more similar to a setup with the propagation of a transtensional discontinuity in the numerical experiments (Fig. 15 and further discussion below). Another set of 3-D experiments (Le Pourhiet *et al.*, 2014) focused on strike-slip shear zones furthermore shows that the presence of a weak lower crust is required to produce a-type domes below strike-slip faults. It has also been shown that a resistant lower crust and resistant upper mantle favor the development of a-type domes in the mantle in the context of development of transform passive margins (Le Pourhiet *et al.*, 2017). This situation could be compared to the early development of the North Baleares Transfer Zone before the installation of a mature volcanic arc but some more detailed studies of the relative timing of the domes and the magmatism would be necessary to sustain this hypothesis.

6.2 Connection with magmatism

The connection with the history of magmatism is clear also in the Aegean-Anatolian region where the formation of the tear in the slab is accompanied with the development of magmatic provinces and migration of plutons due to toroidal asthenospheric flow (Jolivet *et al.*, 2015b; Menant *et al.*, 2016a, 2016b). The migration of magmatism is also clearly visible in the example of the North African margin during the propagation of the tear from east to west and the coeval migration of the deformation in the Tell and Rif orogens (Maury *et al.*, 2000; Duggen *et al.*, 2008) (Fig. 7). The Tyrrhenian Sea shows a similar evolution with very few true strike-slip faults and the development of complex fan-shaped patterns of normal faults and localization of magmatism within the transfer zone on either side of the Marsili basin (Fig. 5). The distribution of the magmatism at the surface is probably controlled by two processes working at different scales. The slab tear in itself provides the high-temperature conditions for melting the mantle (Dilek and Altunkaynak, 2009; Ersoy and Palmer, 2013; Menant *et al.*, 2016a, 2016b; Roche *et al.*, 2018a, 2018b) and the faults in the upper crusts forming above the tear can act as guides for magmatic fluids toward the surface as shown by the case of the Marsili basin and the Diamante-Enotrio-Ovidio volcanic-intrusive complex (De Ritis *et al.*, 2019). The Catalan Transfer Zone is also associated with the underplating of gabbroic rocks below the crust and the whole northeastern part of the Valencia Basin shows the development of a large volcanic province partly controlled by parallel transfer zones (Maillard *et al.*, 2020). Roche *et al.* (2018a, 2018b) show that, in addition to the high heat flow induced by the advection of asthenospheric material above the slab tear, shear heating in the mantle within the tear itself is a significant source of heat to explain large-scale thermal anomalies and lower crustal melting, as in the example of the Menderes massif and part of the Cyclades.

6.3 Ductile deformation and weak crust

The deformation within the transfer zones of the back-arc domain above slab tears is thus rarely localized along pure strike-slip faults. Low-angle shear zone and steep faults oblique to perpendicular to the strike of the transfer zone instead dominate. When the transfer zone has reached a certain stage of development, HT metamorphic domes of a-type are exhumed and magmatic products are emplaced at the surface and at depth.

The numerical models of Le Pourhiet *et al.* (2012) show a vertical partitioning of deformation above a strike-slip system (Fig. 15). These models were designed to test the parameters controlling the formation of a-type domes elongated in the direction of regional stretching above slab tears (see Le Pourhiet *et al.*, 2012, for a detailed description of the initial setups). The model shows the deformation in the crust above faults in the rigid basement (lithospheric mantle). Three different setups were used in these numerical experiments, a purely extensional setup leading to classical b-type domes, a pull-apart setup forming a-type domes and an intermediate setup with the propagation of a strike-slip fault in an extensional domain. The lineation and schistosity in these three suites of experiments were already published in Le Pourhiet *et al.* (2012), but they have been reextracted here according to depth to produce maps that clarify the vertical partitioning of the deformation in the models. The lineation has been projected in the horizontal plane so that the length of vectors is inversely proportional to their dipping angle. What these maps outline most is that, close to the surface, the lineation is always in the direction of regional stretching and the schistosity is flat, while at medium depth the schistosity is vertical with horizontal lineation and at greater depth, the schistosity flattens again while the lineation describes a sigmoid in the horizontal plane,compatible with the sense of shear (left-lateral here). This vertical partitioning can be usefully compared with the Mediterranean examples. Exhumed MCCs in the Aegean show this partitioning between low-angle foliation in the upper structures and steeper foliation deeper. The case of the Naxos dome is exemplary of this behavior with folds with steep axial planes in the core of the dome. The base of the crust is never observed in these Mediterranean MCCs but the rather flat Moho and the apparent coupling between mantle flow and crustal deformation imposes a flat attitude of foliations around the Moho, which is similar to observations in the models. The differences observed in the lineation trend in the Aegean could in fact be simply the consequence of the strike-slip component due to slab tearing, without the need of a strike-slip fault such as the postulated Mid-Cycladic Lineament there to separate two rigid domains with differential rotations as discussed in Le Pourhiet *et al.* (2012). This lineament has been described kinematically as a complex left-lateral strike-slip fault accommodating differential rotation between the western and eastern Aegean (Walcott and White, 1998), a dextral strike-slip fault system (Philippon *et al.*, 2014) or a transtensional feature (van Hinsbergen and Schmid, 2012). The pattern of lineations shown by the numerical models suggests that this structure at the scale of the entire crust may not be necessary.

Following Buck (1991), one can then compare the formation of MCCs above a thin and hot lithosphere with extension in an oceanic environment. The a-type dome forming in the continental crust above a tear fault can also form in the flowing asthenosphere below a nascent transform fault between two ridges (Le Pourhiet *et al.*, 2017) which would be an additional explanation for the coaxiality between crustal stretching and mantle flow suggested by the comparison of field observations and seismic anisotropy in these regions (Jolivet *et al.*, 2009). This distributed deformation contrasts with the extreme localization of evolved oceanic transform faults or the recent localization of the North Anatolian Fault. The concomitance of a distributed deformation, HT domes and magmatic centers plead for a hot and weak crust supported by a weak lithosphere within the transfer zones above the flowing asthenosphere. A weak crust would allow coupling of the deformation with the flow of asthenospheric mantle underneath and thus favor low-angle structures (Sternai *et al.*, 2014; Jolivet *et al.*, 2018). The association of slab retreat, slab tearing and the presence of the volcanic arc favor the development of large-scale thermal anomalies in back-arc regions and thus the ductile behavior of the extending crust (Roche *et al.*, 2018a, 2018b). Well known in the Aegean and the Northern Tyrrhenian Sea where metamorphic core complexes have been described, this ductile behavior is also observed in the transition zone between the Gulf of Lion and Valencia Basin. A wide volcanic province is evidenced offshore during the rifting period and it is located next to the coeval volcanic arc developed in Sardinia at the same period (Jolivet *et al.*, 2019; Maillard *et al.*, 2020). The case of the Alboran Sea is more complex. The main metamorphic core complexes formed after 20 Ma show amphibolite facies rocks but no anatexy. But the western part of the Alboran domain shows evidence of partial melting during extension and intrusion of leucogranites dated from the Early Miocene (Rossetti *et al.*, 2010, 2013). The peak of temperature was attained in the basement of the Alboran Sea recovered during ODP site 976 at around 27 Ma (Comas *et al.*, 1999; Soto and Platt, 1999). It is thus conceivable that a significant part of the Alpujarride units flooring the Alboran Sea have recorded this high-temperature evolution.

A larger-scale perspective of the evolution of transfer zones above slab tears can be obtained from lithospheric-scale 3D numerical models. The 3-D dynamics of the Aegean region or similar settings has been studied through numerical modelling (Capitanio, 2014; Sternai *et al.*, 2014; Menant *et al.*, 2016a, 2016b; Sternai *et al.*, 2016; Roche *et al.*, 2018a, 2018b), showing that slab tearing at depth has a strong impact on strain localization in the back-arc basin. The model of Sternai *et al.* (2014), in particular, shows the localization of a strike-slip shear zone comparable to the North Anatolian Fault and the CHSZ joining the trench. Roche *et al.* (2018a, 2018b) show in addition the formation of domes in the back-arc region as a consequence of crustal-scale boudinage. A more detailed analysis of the models of Menant *et al.* (2016a, 2016b) (Fig. 16) shows the coeval formation of b-type and a-type domes. This model uses a 600-km deep box and a simplified rheology with a 50-km thick one-layer granitic crust in the continental upper plate, with the lower crust partially molten (see details of the setup in Menant *et al.*, 2016a, 2016b). The down-going plate carries a continental block on the right side and is only oceanic on the left side. A slab detachment is observed where continental lithosphere is subducted and fast retreat of the oceanic slab on the left side induces the formation of a back-arc basin. Figure 16A shows the 3-D flow of mantle underneath as red arrows and flow of crustal material as black arrows, which results from this fast slab retreat and tearing. In the overriding plate, a wide strike-slip shear zone develops above the tear in the slab. Figure 16B shows the depth of the top of the molten crust, highlighting the formation of domes, which are detailed in map view on Figure 16C. Deformation associated with these domes are represented as finite strain ellipsoids calculated for the upper and lower crusts. One then sees a dome elongated perpendicular to the long axis of strain ellipsoids away from the slab tear (b-type dome) and domes parallel to the long axis of strain ellipsoids right above the slab tear (a-type domes). As in the higher-resolution crustal-scale experiments of Le Pourhiet *et al.* (2012) the lower crust, here partially molten, shows a vertical foliation in the core of the domes and an low-angle foliation in the upper crust, a situation reminiscent of the Naxos metamorphic core complex.

6.4 Evolution toward a new plate boundary

The case of the CHSZ should be considered separately as it is the western extension of a major plate boundary propagating in the Aegean domain, the North Anatolian Fault. The Central Hellenic Shear Zone shows the present-day development of a such a transfer zone. No strike-slip shear zone is observed except in the trench area or the proximity of the NAF. Rotating parallel normal faults are instead observed. The connection between these steep recent faults and the earlier detachment in the case of the Corinth Rift is not entirely clear but it could correspond to two successive stages. Finally, the extreme localization is shown by the North Anatolian Fault and the North Aegean Trough where a pure strike-slip system is currently developing, witnessing a possible future plate boundary connecting with the Hellenic Trench. This major fault originates from the conjunction of two main drivers, the Arabia-Eurasia collision inducing escape tectonics and slab retreat/tearing forming a wide transfer zone across the Hellenides. The domain where the NAF propagates, *i.e.* the North Aegean Trough was once part of the internal Hellenides and the crust there was thick and warm, as shown by the HT metamorphic domes observed on Thasos and the associated granitic intrusions. With time, the trench retreated and the volcanic arc followed toward the south. The back-arc domain situated at some distance of the volcanic arc thus cooled down through time. This might explain the extreme strain localization of strain and formation of a true strike-slip fault in the Marmara Sea and North Aegean Trough once the crust had thinned. As the magmatic arc and the uprising asthenosphere are close to the deforming region, the lithosphere is thin and hot and the thick crust behaves ductilely. Once the region has cooled down and the crust has been significantly thinned, the mantle returns to a more resistant behavior and the NAF can propagate as a strike-slip fault until the transition with the region where the crust is thicker and hotter. The progressive thinning of the continental crust in the hot region by a complex association of normal faults and metamorphic core complexes is replaced by a simpler strike-slip system.

7 Conclusions

This review of the structures observed within transfer zones in the Mediterranean back-arc regions above slab tears reveals a particular behavior of the continental crust.

Unexpectedly, no major strike-slip system is formed in a first stage. Low-angle extensional shear zones exhuming a-type metamorphic domes with their axes parallel to the regional stretching direction are instead observed within these wide transfer zones. En-échelon disconnected strike-slip faults may form, as in the case of the North African margin, but they are not connected into a single large-scale strike-slip fault. Once the system has evolved toward significant crustal thinning and in the far back-arc domain a true strike-slip fault can form and evolve into a localized plate boundary, shown by the example of the North Anatolian Fault.

Transfer zones above slab tears are furthermore associated with intense magmatic activity and H*T* metamorphic core complexes. The lower crust within the transfer zones can be molten, leading to the formation of H*T* metamorphic core complexes because of the additional heat flow due to the advection of asthenospheric material above the tear and also because of intense shear heating in the tear itself. Arc magmatism is focused and dragged in the transfer zones by the asthenospheric flow. Part of this magmatism can remain underplated in the lower crust without major expression at the surface like in the example of the Catalan transfer zone.

The conjunction of a high heat flow and intense magmatic activity leads to strong weakening of the crust and hampers the formation of a localized strike-slip system, instead favoring low-angle extensional shear zones controlling transtension basins. Within the partially molten lower crust, the finite strain can be constrictional and folds with vertical axial planes then form in the core of MCCs.

Transfer zones in back-arc domains above slab tears thus have various expressions in the crust but they are never simple strike-slip systems, rather wide zones of lateral gradients of extension and a-type metamorphic core complexes in the middle and lower crust, while the upper crust shows discontinuous short strike-slip faults, transtensional basins or low-angle detachment and supra-detachment basins. It is only once the system has evolved toward significant crustal thinning in the far back-arc domain that a true strike-slip fault can eventually form and evolve into a localized plate boundary.

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