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Oblique rifting triggered by slab tearing and back-arc extension : the case of the Alboran rift in the eastern Betics

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Abstract

The tectonic evolution of highly oblique continental margins that result from back-arc extension above lithospheric STEP faults is poorly understood. Here, we investigate the case of the Alboran margin in the eastern Betics characterized by crustal thinning of 15-10 km, oblique to the direction of slab retreat. The current deformation patterns indicate that oblique back-arc rifting is underway. However, it is unclear whether these conditions are those that prevailed during the formation of the metamorphic domes and intramontane basins. We review the temporal and spatial evolution of Neogene sedimentary basins and brittle deformation in the eastern Betics, and exploit offshore seismic reflection lines to propose a crustal-scale section across the oblique margin. The history of sediment infill and rates of subsidence combined with the analyses of fault slip data, confirm that brittle extension oriented from N20°E to EW occurred during an interval spanning from the Serravallian-early Tortonian to the late Tortonian (14-8 Ma). This extension is found associated with both normal and strike-slip regimes and the evolution of the strike-slip corridors flanking the metamorphic domes. The transtensional model forms a coherent scheme linking the ductile deformation associated with metamorphic domes and the formation of EW- and NW-SE/NNW-SSE-directed sedimentary basins in the brittle upper crust during the Tortonian. The oblique extension, which is closely associated with STEP faulting, occurred during the regional convergence between Africa and Iberia since the Miocene. Only recently, around 8 Ma, the slab detached, leading to local tectonic inversion. Such a type of narrow oblique rifted margin associated with transform-like plate boundaries is not unique but is expected to be hardly preserved in the geological record due to the transient nature of retreating subduction systems.

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1 Tear faulting and the formation of oblique transform margin in the Betics

Lithospheric tear faults or subduction-transform edge propagator (STEP) faults are propagating strike-slip faults that accommodate the differential motion between the retreating subduction zone and the overriding back-arc plate (Govers and Wortel, 2005). Because of the relative motion between back-arc and surrounding plates, they are also propagating strike-slip faults defined by a sharp contrast in crustal thickness. As noted by Govers and Wortel (2005) such oblique fault boundaries do not necessarily form proper transform plate boundaries but broad zones of distributed deformation, accommodating differential trench-parallel extension, strike-slip motion and rotation. In case the lithospheric tear propagates within the continent-ocean transition, a narrow continental margin forms highly oblique to the direction of back-arc extension. This is documented, for instance, in the Carribean, along the transcurrent Carribean-South America plate boundary (Pindell and Kennan, 2009) or on the margin of the South Orckney microcontinent, along the Scotia-Antarctic plate boundary (Dalziel et al., 2013). Despite the large-scale kinematic picture is relatively well understood, there are only few places where continental crustal deformation associated with this peculiar type of slab-edge continental rift system can be studied.

Here, we focus on the Betic Cordillera, on the northern boundary of the Gibraltar arc (**Figs 1 and 2**). There, a rifted margin, defined by decreasing crustal thickness from 35 to 20 km in the Abloran basin (Diaz et al., 2016), is seen to develop above a STEP fault (Badji et al., 2014; Gallais et al., 2013; Jolivet et al., 2021a; Mancilla et al., 2015a). The tectonic expression of the transcurrent deformation during crustal extension above the lithospheric tear is however controversial. On the one hand, low-angle ductile extensional detachments with a top-to-the-west sense of shear are the main features accommodating deformation in the overriding plate. Yet, a-type metamorphic domes in the lower crust, elongated parallel to the E-W direction (**Fig. 1**), are viewed to express the transtensional deformation at the tip of propagating tear (Pourhiet et al., 2012). On the other hand, strike-slip faulting is interpreted as a late brittle deformation feature associated with E-W crustal strike-slip brittle faults between the metamorphic domes in the eastern Betics (Alpujarras corridor ; Sanz de Galdeano and Vera, 1992; Sanz de Galdeano et al., 1985; Martínez-Martínez et al., 2006) and in the western Betics (e.g. Torcal corridor ; Frasca et al., 2016) unrelated to ductile deformation (**Fig. 1**). In line with the latter interpretation, the dextral motion these strike-slip faults accommodate is assumed to be modest, reflecting a recent post-8 Ma kinematic change that accompanies the end of slab retreat, and onset of compression in the Gibraltar Arc (Do Couto et al., 2014; d'Acremont et al., 2020; Jolivet et al., 2021a; Martínez-García et al., 2017).

The lack of structural, temporal constraints and quantification of belt-parallel motion along these faults indicates, however, that we do not yet fully understand their link with the long-term evolution of slab tearing and margin formation. For instance, the current deformation patterns brings critical evidence that both strike-slip faulting and extension operate synchronously, so that brittle strike-slip faulting and ductile extension might reflect the same tectonic episode. This is argued by ongoing extension illustrated by the west-directed GPS velocities increasing westwards, and the west-directed displacements increasing towards the Alboran domain revealing active right-lateral shear deformation (**Fig. 2**). The current transtensional deformation across the Betic Cordillera is also shown by the current stress regime defined by extension direction highly oblique (max. 20°) to the Betic structural trend (or 70° spanned by the direction of extension and normal of the rift trend). Right-lateral transtensional deformation in the

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Betic agrees with evidence for west-directed lateral extrusion of the Alboran Basin (Borque et al., 2019; Palano et al., 2015). In the east, the extrusion is accommodated by left-lateral strike-slip displacement along the Eastern Betic Shear Zone (EBSZ; Borque et al., 2019), which is shaped by the Carboneras Fault (CF) and Palomeras Fault (PF). This fault extends offshore, across the Alboran Sea, in the larger Trans-Alboran Shear Zone (De Larouzière et al., 1988; Stich et al., 2006) moving at ~4 mm/yr, equivalent to the regional 5 mm/yr NW-directed convergence between Africa (Nubia) and Europe (**Fig. 2**; Echeverria et al., 2013; Koulali et al., 2011; Nocquet, 2012; Palano et al., 2015, 2013; Vernant et al., 2010). Here, we hypothesize that the present-day oblique extension patterns is at play since the Miocene and explain the formation of the narrow Alboran rifted margin.

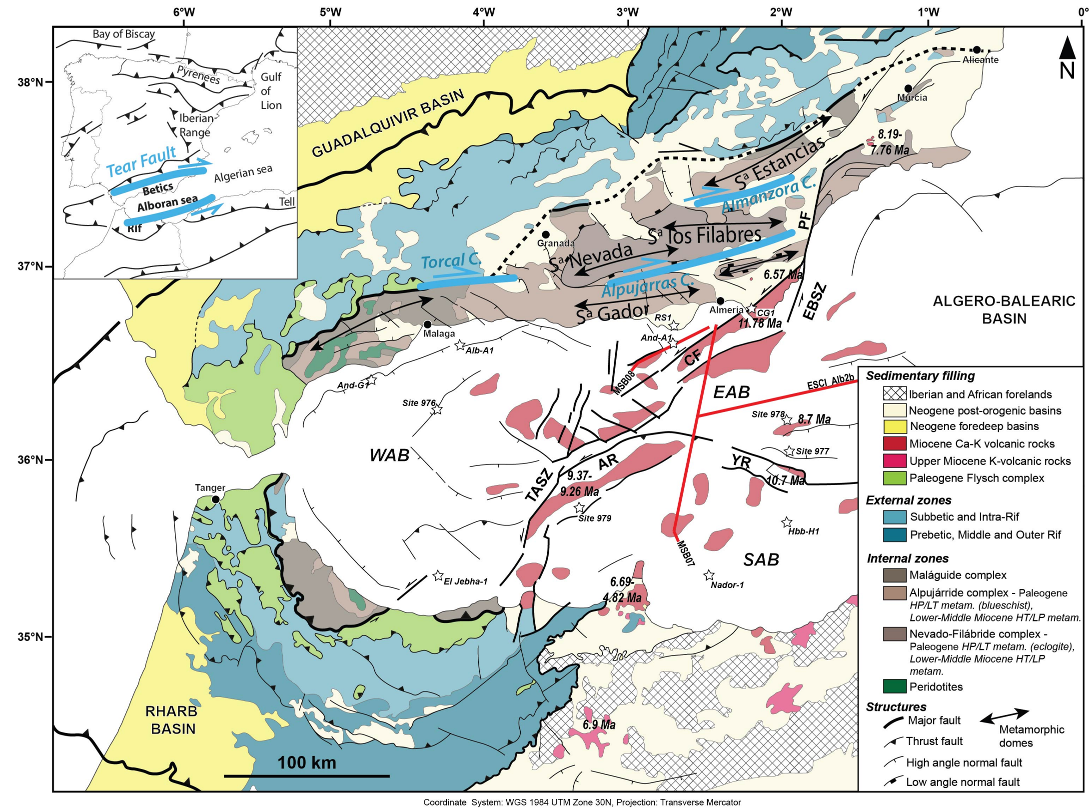

Figure 1 : Geological map of the Betic-Rif arc. Main tectonic units and age of volcanism as well as major structures and Neogene sedimentary basins are shown. The studied offshore seismic lines (red) is displayed as well as offshore wells and ODP sites (★) for stratigraphic calibration in the East (EAB), South (SAB) and West Alboran basins (WAB). CF: Carboneras Fault; PF : Palomeras Fault; AR: Alboran Ridge; YR: Yusuf Ridge; EBSZ : East Betic Shear Zone; TASZ: Trans-Alboran Shear Zone.

Only recently high-resolution 3D numerical models have been able to predict the deep structure of oblique rift domains. These models can be used as a guide to re-evaluate the evolution of the Betic region. 3D models by Jourdon et al. (2021) predict that oblique extension results in narrow rifted margins, strike-slip faults and corridors coupled

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with subsident pull-apart basins, normal faults and block rotations (**Fig. 3**). The recognition of block rotation in the Betic arc (Crespo-Blanc et al., 2016; Platzman, 1992), strike-slip corridors (**Fig. 1**) and NW-SE normal faulting, which defines extension direction highly oblique to the margin, (Galindo-Zaldivar et al., 2003; **Figs 1 and 2**) all support this view. The simulations of Jourdon et al. (2021) also show that the deeper ductile crust experiences thinning (vertical flattening) and stretching perpendicular to the strike of the margin in accordance with stretching lineations parallel to the metamorphic domes and low-angle detachments (**Fig. 3**). Other types of 3D numerical experiments show that sediment loading of strike-slip faults can result in assymetric flexural basin with apparent normal fault throw (Neuharth et al., 2021) that can be mistakenly interpreted as resulting from orthogonal extension. Asymmetric basins are indeed intriguing characteristics of intramontane basins in the Betics (Augier et al., 2013; Do Couto et al., 2014). Although primarily found associated with divergent plate boundaries e.g. in the Gulf of California (Fossen et al., 2013; Fossen and Tikoff, 1998) highly oblique extension is also documented in active transform regions along the San Andreas Fault (Teyssier and Tikoff, 1998) or the North Anatolian Fault in Marmara Sea (Okay et al., 2004). A detailed analysis of highly oblique rifting deformation in the Gulf of California recognises similar tectonic elements as for the Betics, such as extensional detachment systems orthogonal to the divergence and upper crustal folds trending parallel to the divergence (Fossen et al., 2013).

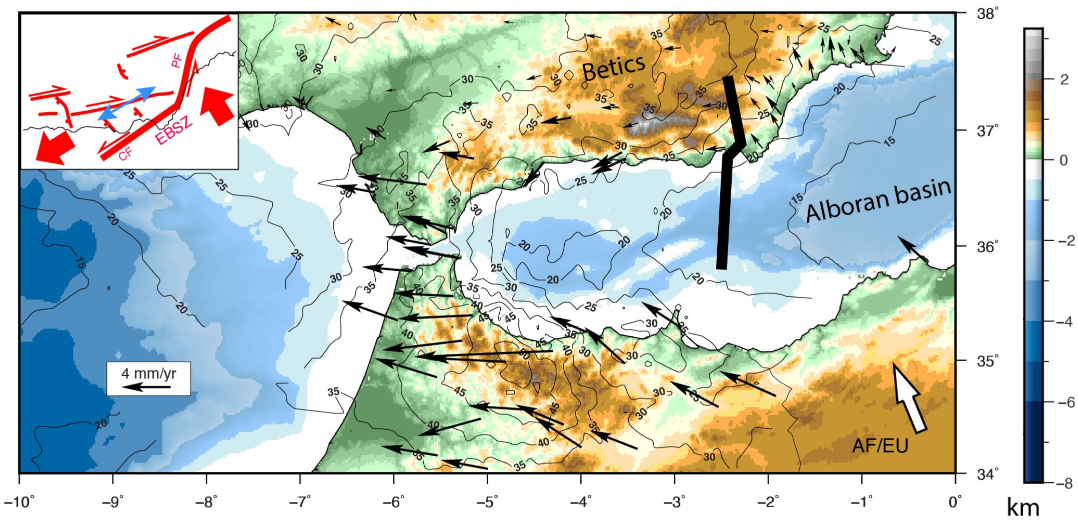

Figure 2 : Present-day kinematics in the Betic-Rif arc and eastern Betic Cordillera (inset). GNSS-based displacements in the Abloran block and northern Africa shown in a fixed Eurasian reference frame (black arrows after Palano et al., 2015) are oblique to the AF/EU plate convergence (white arrow) inferred from plate tectonic Morvel model (Argus et al., 2011). Labelled contours depict the crustal depth given in kilometers as inferred from deep seismic profiles and receiver functions analysis (Diaz et al., 2016). In the eastern Betic (inset), W-directed stretching is taken up by EW-directed right-lateral strike-slip fault and NW-SE normal faults. Extension direction resolved from focal mechanisms (blue arrows) are after (Stich et al., 2006). CF: Carboneras Fault; PF : Palomeras Fault; AR: Alboran Ridge; YR: Yusuf Ridge; EBSZ : East Betic Shear Zone; TASZ: Trans-Alboran Shear Zone.

Several tectonic features need further discussion however. First, the relevance of strike-slip faulting in the past is debatable as only a few occurrence of crustal-scale strike-slip faults are mapped. Second, the detail of the temporal

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and spatial relationships between the formation of the oblique/transform margin and STEP faulting remain elusive. We here review the temporal and spatial evolution of Neogene intramontane sedimentary basins and related brittle deformation in the eastern Betics. In addition, we exploit offshore seismic reflection lines to propose a new crustal-scale section across the oblique margin. Based on these constraints we present a tectonic scenario for the formation of the high-obliquity rift margin in back-arc setting controlled by STEP faulting.

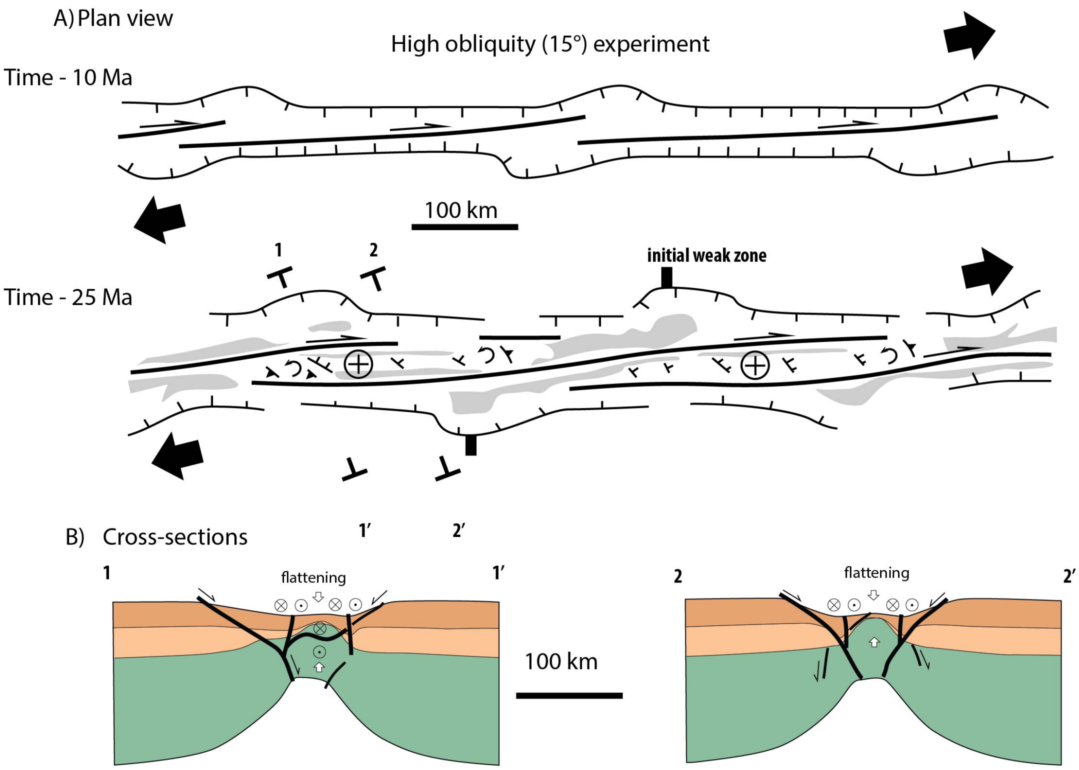

Figure 3 : Sketch showing two steps (after 10 Myrs and 24 Myrs) of a 3D thermo-mechanical model of oblique rifting in plan view (A) and cross-sections (B). Results are redrawn after (Jourdon et al., 2021) for the case of a highly oblique experiment where extension is set with an angle of 15° with respect to the rift axis. Grey regions in (A) are basins adjacent to uplifted domains (cross-circle symbol) associated with right-lateral strike-slip faults. Cross-sections (B) depict the abrupt crustal thinning that occur perpendicular. Crustal thining is most visible for the lower crust and produces the formation of an abrupt necking domain controlled by rift-parallel normal faults dipping towards the center of the rift and right-lateral strike-slip faults.

2. Geodynamics and STEP faulting in the Betics

The onset of N-directed movement of Africa, by the Late Cretaceous-Paleogene, led to a Laramide-like contraction from Morocco throughout Western Europe (Mouthereau et al., 2021). South of Iberia, in the Betic-Rif domain, the closure of hyper-extended rift systems and oceanic basins of the Atlantic-Alpine Tethys resulted in the development of a proto-Betic accretionary prism, likely largely submerged (Angrand and Mouthereau, 2021; Daudet et al., 2020; Vergés and Fernàndez, 2012). By about 50 Ma, the acceleration of plate convergence led to the shortening of

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continental rift and oceanic basins and topographic uplift all over Iberia (Daudet et al., 2020; Mouthereau et al., 2021, 2014; Rat et al., 2019; Vacherat et al., 2016; Waldner et al., 2021) associted with onset of continental rifting along the Western European Rift (e.g. Mouthereau et al., 2021). 35 Ma ago, as Africa convergence slowed down, the western Mediterranean sea opened accompanied by retreating slabs (Dewey, 1988; Dewey et al., 1989; Faccenna et al., 2014; Jolivet and Faccenna, 2000; Rosenbaum et al., 2002). Subduction occurred mainly before 30 Ma as argued by age constraints on high-pressure mineral assemblages (Romain Augier et al., 2005a; Bessière et al., 2021; Booth-Rea et al., 2015; Gomez-Pugnaire and Fernandez-Soler, 1987; Platt and Vissers, 1989; Platt and Whitehouse, 1999) and has been suggested to last until the mid-Miocene in the eastern Betics e.g. (Platt et al., 2013). The timing of formation of the Alboran basin is constrained to 23 to 16 Ma by the oldest deposits found on Alboran basement and by the timing of high-temperature metamorphic overprint and rapid cooling to shallow crustal temperature (Bessière et al., 2021; Daudet et al., 2020; Janowski et al., 2017; Johnson et al., 1997; Platt et al., 2005; Sosson et al., 1998; Vázquez et al., 2011; Zeck et al., 1992).

All kinematic reconstructions agree that extension results from the westward migration of the arc front and retreat of the Alboran slab, well imaged below the Gibraltar arc as a steeply-dipping high-velocity anomaly (Bezada et al., 2013; Heit et al., 2017; Mancilla et al., 2018, 2015a, 2015b; Palomeras et al., 2014; Spakman and Wortel, 2004; Villaseñor et al., 2015). These reconstructions, however, differ according to the paleo-position of Alboran terrane, and hence to the amount and vergence of subduction (Angrand and Mouthereau, 2021; Hinsbergen et al., 2014; Lonergan and White, 1997; Romagny et al., 2020; Rosenbaum et al., 2002; Vergés and Fernàndez, 2012). Seismic tomography reveals that slab detachment and tearing occur along the conjugate Alboran margins of the southern Betics and northern Africa (Govers and Wortel, 2005; Heit et al., 2017; Mancilla et al., 2015a; Meighan et al., 2013; Spakman and Wortel, 2004).

In **Fig. 4** we refer to the reconstruction of Angrand and Mouthereau (2021) that has the advantage of reconciling previous western Mediterranean models (Romagny et al., 2020; Vergés & Fernàndez, 2012) with recent thermochronological analyses in western Betics (Daudet et al., 2020) and other geological data (see compilation in Mouthereau et al., 2021). This model accounts for the existence of an upper Cretaceous-Paleogene foreland basin that formed adjacent to a proto-Betic orogen. In this reconstruction about 400 km of slab retreat is estimated since about 35 Ma (gray path, blue arrows in **Fig. 4**). It is worth noting that for Romagny et al. (2020) a similar amount (i.e. 400 km) is accommodated by back-arc extension of the Alboran crust, implying the same magnitude of displacement along the STEP fault in the Betics. In the reconstruction of Angrand and Mouthereau (2021), however, crustal thinning in Alboran basin is linked to delamination retrat of the Alboran lithospheric mantle towards the west. In such a model, because of the decoupling between crust and mantle, the length of the delaminated slab resolved at depth in seismic tomography, should not be simply translated into the amount of crustal extension in the Alboran domain. This further implies the displacement across the STEP fault must be also less than 400 km. Daudet et al. (2020) suggested that an extension of 110 km estimated from the restoration of low-angle detachment systems in the central and eastern Betics (Martínez-Martínez et al., 2002) is likely to be a more accurate crustal estimate of the movement Alboran domain ratehr than the total slab length.

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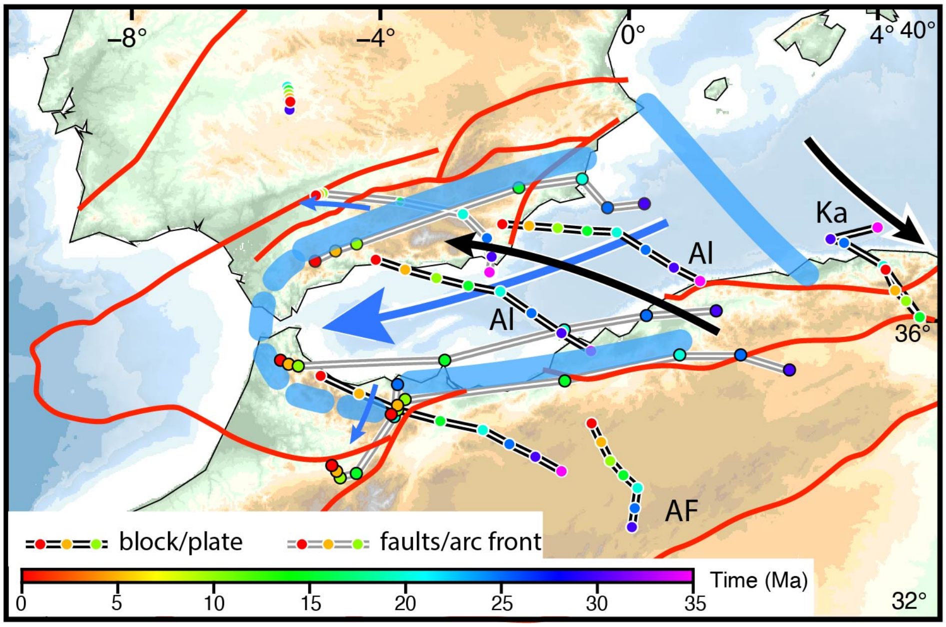

Figure 4: Kinematics of African plate (AF), Alboran (Al) and Kabylides (Ka) blocks with respect to fixed European plate since 35 Ma reconstructed after Angrand and Mouthereau (2021). Thick blue lines depicts the position of lithospheric tear faults (between Al and Europe and Africa) and transfer faults (between Al and Ka). Black arrows indicate the regional movement of Al and Ka with respect to Europe along black motion paths presented from 35 Ma to present. Grey motion paths refer to the motion of specific structures relative to Europe, including the motion of the arc front (thick blue dashed line) and faults in red. Dark blue arrow depicts the movement of the arc front due to retreating delamination towards the west.

3. Miocene extension in the eastern Betics

3.1 Relationships between domes and basins : from transtension and pure extension to late tectonic inversion

The most prominent extensional features in the eastern Betics are : 1) E-W elongated ranges that formed metamorphic domes with foliations bearing prominent E-W stretching lineations (**Fig. 5**; e.g. Sierra de los Filabres-Sierra Nevada, Sierra de Gador and the Sierra de las Estancias) and Serravallian-Tortonian sedimentary basins (Tabernas-Sorbas, Alpujarras, Almanzora and Huércal-Overa basins); 2) NNW-SSE/NW-SE normal fault systems and basins oblique to the domes such as the NW-SE trending Guadix-Baza and Alhabia basins (Galindo-Zaldivar et al., 2003; Martínez-Martínez and Azañón, 1997) (**Fig. 5**). They are described as asymmetric half grabens (Do Couto et al., 2014; Martínez-Martos et al., 2017; Pedrera et al., 2010, 2009) formed during the Upper Serravallian-Early Tortonian (Augier et al., 2005b; Augier et al., 2013; Meijninger and Vissers, 2006). Several of these NW-SE faults are active and cut across the metamorphic domes and the sedimentary basins (Augier et al., 2005a; Booth-Rea et al., 2004; Giaconia et al., 2012; Montenat and Ott d'Estevou, 1999).

In addition to these structures there are E-W right-lateral strike-slip faults that define structural corridors, like the Alpujarras corridor/basin between the Sierra de Gádor and the Sierra Nevada, and the Almanzora corridor/basin between the Sierra de los Filabres and Sierra de las Estancias (**Fig. 5**). The left-lateral Carboneras and Palomeras fault

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system (Reicherter and Hübscher, 2006; Scotney et al., 2000) marks the tectonic limit with the Cabo de Gata volcanic province (**Fig. 5**).

The domes are extension-related features interpreted either as 1) EW-metamorphic domes resulting from the exhumation in the footwall of a regional W-directed extensional low-angle detachments, later folded during post-Tortonian N-S contraction (e.g. Montenat & Ott d'Estevou, 1990; (Sanz de Galdeano and Vera, 1992; Sanz de Galdeano and Alfaro, 2004; Martínez-Martínez et al., 2002; Martínez-Martos et al., 2017; Pedrera et al., 2010, 2007) or 2) Miocene metamorphic domes formed by constrictional ductile strain regime accompaniying W-directed stretching of the Alboran domain and trench retreat, with limited overprint by the Tortonian contraction ca. 8 Ma (Augier et al., 2013; Augier et al., 2005; Augier et al., 2005b; Galindo-Zaldivar et al., 2015; Jolivet et al., 2021b; Martínez-Martínez et al., 2002). Low-temperature constraints from the Nevado-Filabride and Alpujarride complexes confirm the west-directed exhumation of the basement that occurred progressively from the Sierra de los Filabres at ~13-11 Ma (Serravallian) in the East to the Sierra Nevada at 8-6 Ma (Tortonian) in the West (Clark and Dempster, 2009; Janowski et al., 2017; Johnson et al., 1997; Platt et al., 2005; Reinhardt et al., 2007; Vázquez et al., 2011).

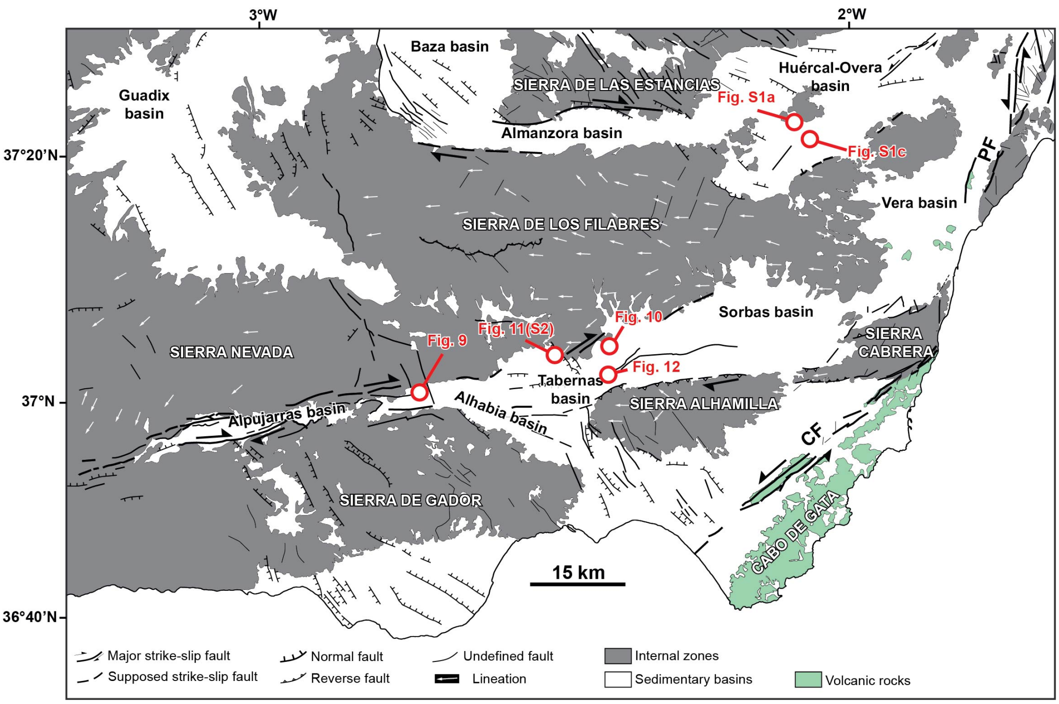

Figure 5 : Tectonic map of the eastern Betics showing the main structural elements in black after Augier et al. (2005) and Do Couto (2014). CF: Carboneras Fault; PF : Palomeras Fault.

Tectonic models for the formation of Neogene intramontane sedimentary basins vary depending on the prevailing tectonic regime. EW-directed basins have been early described as pull-apart basins (e.g Alpujarran corridor) (Sanz de Galdeano et al., 1985). Structural analyses then led to re-interpret these structures as transfer zones resulting from differential extension between exhuming core-complexes (and detachment systems) since the Serravallian (13-11 Ma) later refolded during Tortonian (9-8 Ma) compression (Martínez-Martínez et al., 2006). In support to the dominant regional compressional stress regime, Martínez-Martos et al. (2017) proposed the E-W depressions are related to the tectonic reactivation of crustal weakness zone as dextral strike-slip faults in a counterclockwise rotation, accommodating part of the the N-S shortening. There are evidence that at the end of the Tortonian a regional uplift occurred, rising the remnants of late Tortonian marine platform, 7.2 Ma in age, to 1600 m above sea level in the Sierra de Gádor (Braga et al., 2003; Janowski et al., 2017), coincidently with the onset of contraction in the Sierra Alhamilla and Sierra de los Filabres (e.g. Do Couto et al., 2014), in the Alboran domain (e.g. (Martínez-García et al., 2017) and on the margins of the eastern Betic (Giaconia et al., 2013).

Based on the prevalence in some EW-trending basins, like the Huércal-Overa basin, of EW-trending normal faults, these basins have alternatively been interpreted as resulting from late exhumation stage of the domes, possibly as soon as the Serravallian, but mostly after the early Tortonian (syn-sedimentary faulting) (Augier et al., 2013; Romain Augier et al., 2005b; Meijninger and Vissers, 2006). The NW-SE/NNW-SSE sedimentary basins (Guadix, Baza, Alhabia; **Figs. 5**), in contrast, are extensional basins formed parallel to the direction of the regional compression (Sanz de Galdeano and Vera, 1992; Larouzière et al., 1988). E-W strike-slip corridors, aligned in the direction of the domes, and NW-SE normal faulting patterns are both key features consistent with predictions from models of oblique extension at transform margin (**Fig. 3**). Yet, based on existing structural and tectonic syntheses a clear temporal relationships between E-W ductile stretching in the domes and transcurrent deformation is not established (**Fig. 5**).

3.2 Are the Tortonian rift-related subsidence consistent with oblique extension ?

The stratigraphic architecture and depositional evolution of Tortonian intramontane basins provides first-order informations on the distribution of crustal thinning. The oldest sediments deposited unconformably on the Paleozoic-Triassic basement are red alluvial conglomerates and deltaic series dated from Serravallian to lower Tortonian (~11-9 Ma) (**Fig. 6a**). These continental deposits are thicker and well exposed on the flanks of the Almanzora basin and on the northern Huércal-Overa basin (HOB), compared to the Alpujarras Corridor (AC) and Tabernas basin (TB) (**Figs. 6 and 7a**; Augier et al., 2013; Pedrera et al., 2010, 2007; Poisson et al., 1996).

Paleogeographic reconstructions indicate they were deposited on a large emerged domain, stretching from Huercal-Overa to Granada, in the West and in Tabernas, to the South (Braga et al., 2003). Sourced from the Nevado-Filabride metamorphic complex (Hodgson and Haughton, 2004; Kleverlaan, 1989; Meijninger and Vissers, 2006; Pedrera et al., 2010, 2007; Pickering et al., 2001; Weijermars et al., 1985) these deposits mark the onset of surface exhumation of the Sierra de Las Estancias and Sierra de Los Filabres.

During this intial stage, HOB is the most subsident basin (**Figs. 6b, 7a and 7b**), accumulating sediments at rates of 400 m/Ma while rates are 140-180 m/Ma in the Tabernas basin (**Fig. 6b**) (Augier, 2005). Higher subsidence in the HOB, which also started earlier than in other basins, suggests extension occurred originally to the North associated with the exhumation of the Sierra de Las Estancias. Basal continental conglomerates are overlain by grey coarse-grained Tortonian sandstones found occasionally, e.g. in the Almanzora basin, intercalated with marine marls (**Figure**

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6a). They are topped by mid-Tortonian bioclastic calcarenite and coral reefs (Braga et al., 2003; Martin et al., 1989; Pedrera et al., 2007).

During the same interval, TB recorded the deposition of 300 to 400 m of coarse to medium-grained deltaic marine clastics overlying unconformably the lowermost red series (**Fig. 6a**). These sediments pass upwards, e.g. in TB, to deeper marine 1200 m-thick turbiditic and marls series intercalated with regional-scale megabeds, revealing the onset of rapid tectonic subsidence (Haughton, 1994; Kleverlaan, 1989, 1987; Pickering et al., 2001; Weijermars et al., 1985). Details of depositional architecture of the Tortonian suggest that part of this subsidence evolution was controlled by E-W directed strike-slip faults (Haughton, 2000) under transtensional strain.

The transition from continental to deep marine sedimentary environments (water depth of 400-600 m according to Poisson et al., 1999) witnesses the rapid rift-related tectonic subsidence achieved during the upper Tortonian times (~9 Ma; **Figs. 6** and **7c**) (Romain Augier et al., 2005b; Montenat and Ott d'Estevou, 1992; Weijermars et al., 1985). At around 8 Ma, accumulation rates drop by a factor of two to 200 m/Ma in HOB and 70 m/Ma in TB, revealing a marked reduction in subsidence. Subsidence then became negative as basement uplifted from around 7 Ma (**Figs. 6b** and **7d**) in both TB and HOB.

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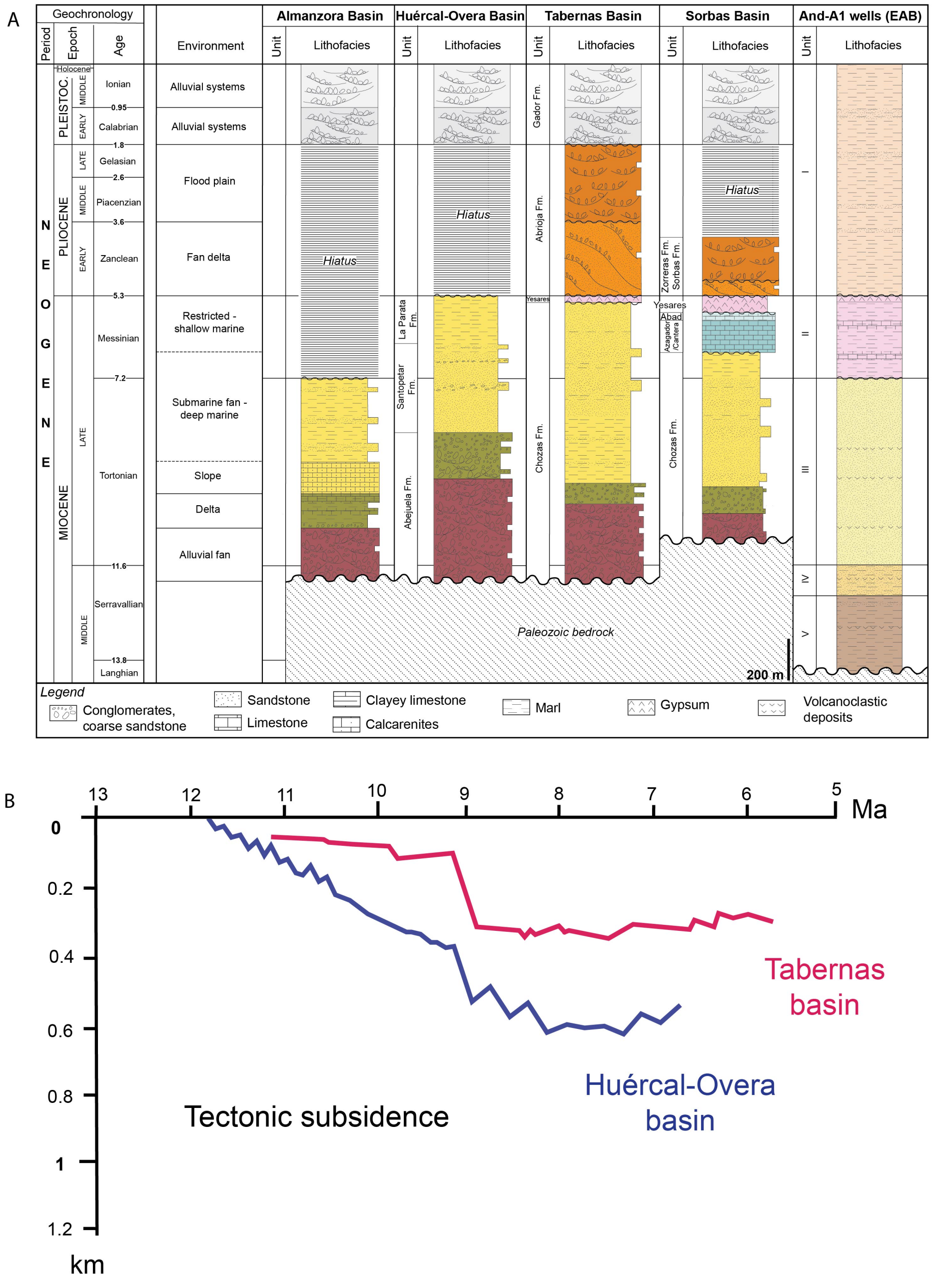

Figure 6 : Stratigraphic evolution and lithologies of intramontane basins in the eastern Betics and offshore A1 well. (a) Neogene stratigraphy and basin-fill correlation in the Almanzora and Huercal-Overa basins (Mora, 1993), Tabernas basin (Hodgson and Haughton, 2004; Kleverlaan, 1989; Pickering et al., 2001) and Sorbas basin (Fortuin and Krijgsman, 2003; Martín and Braga, 1994; Riding et al., 1998). Middle Miocene sedimentary environments in the Alboran Sea are after (Comas et al., 1992). (a) Neogene tectonic subsidence evolution for Tabernas basin and Huércal-Overa basin are from (Augier, 2004). The curves are obtained from backstripping techniques incorporating local eustatic and paleobathymetric corrections.

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The geometry of the Almanzora (Pedrera et al., 2009), Sorbas (e.g. Do Couto et al., 2014) and Huércal-Overa basin basins (Pedrera et al., 2010) inferred from gravity measurements indicate that these basins are asymmetrical and deepening southwards (**Fig. 5**). This sediment infill pattern recalls the formation of asymmetrical basins predicted by numerical models of flexural strike-slip basins (Neuharth et al., 2021). According to this model, the asymmetry observed should reflect the developement of strike-slip basins loaded by sediments originated from the North. In addition, a larger subsidence in HOB is an indication of abrupt crustal thinning to the south of Sierra de las Estancias where the crustal thickness of 35 km is the largest (**Fig. 2**). Therefore, at least the Serravallian-Tortonian infill patterns agree with oblique extension.

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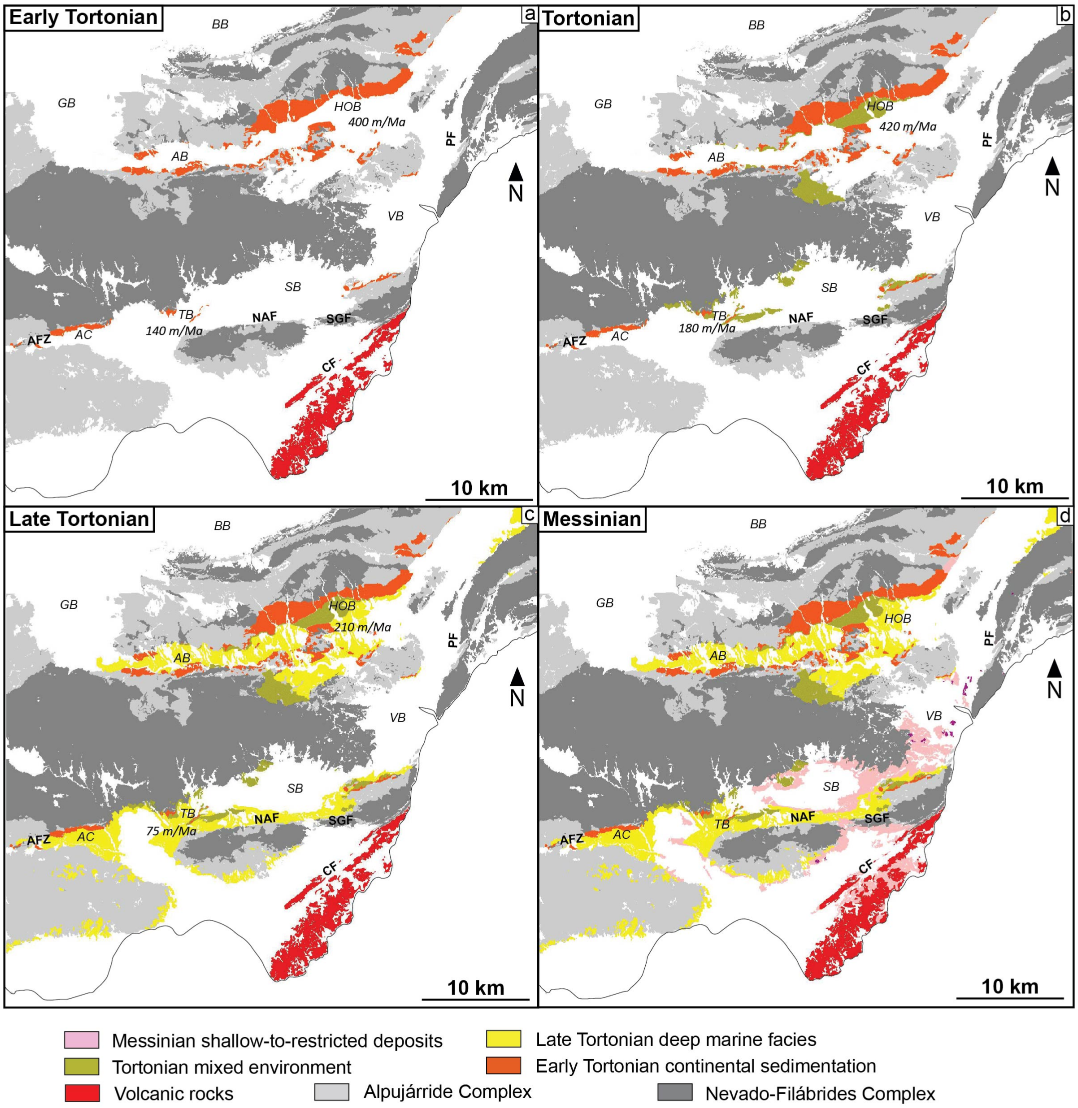

Figure 7: Distribution of (a) lower Tortonian, (b) Tortonian, (c) upper Tortonian and (d) Messinian deposits based on geological mapping of the different basins. CF: Carboneras Fault; PF : Palomeras Fault; SGF: South Gafarillo fault; NAF: North Alhamilla fault; AFZ: Alpujarras fault zone; BB: Baza basin; GB: Guadix basin; AB: Almanzora basin; HOB: Huercal-Overa basin; VB: Vera basin; SB: Sorbas basin; TB: Tabernas basin; AC: Alpujarras corridor.

4. Brittle faulting : pure extension versus transtensional deformation in Neogene basins

4.1. Tectonic regime in the eastern Betics

Figure 8 presents a compilation of 112 fault slip data inversion previously analysed in the eastern Betics combined with new measurements conducted in the Alpujarras Corridor and in the Tabernas basin (**Table S1**). Most faults are syn-Tortonian or cut through the Tortonian. This compilation emphasizes a regional trend of σ3 stress axes oriented

NNE-SSW (N20°E) with subbordinate σ3 oriented E-W. In details, this well-defined regional horizontal extension reflects a combination of pure normal faulting regime (σ2 horizontal and oriented NW-SE/WNW-ESE) and strike-slip faulting regime (σ2 vertical to steeply-dipping and σ1 horizontal an striking NNW-SSE). N-S to NW-SE compression is also reported in the HOB associated with incipient synform and depocenter which is dated to the lower Tortonian coeval with the prominent EW/WSW-ENE extension (e.g. Pedrera et al., 2010).

We describe below, based on a selection of oucrops in the vicinity of the contact between Tortonian basins and major metamorphic domes, the expression of EW and NW-SE extensional faulting in the field. We then discuss how they are linked to the regional stress regimes.

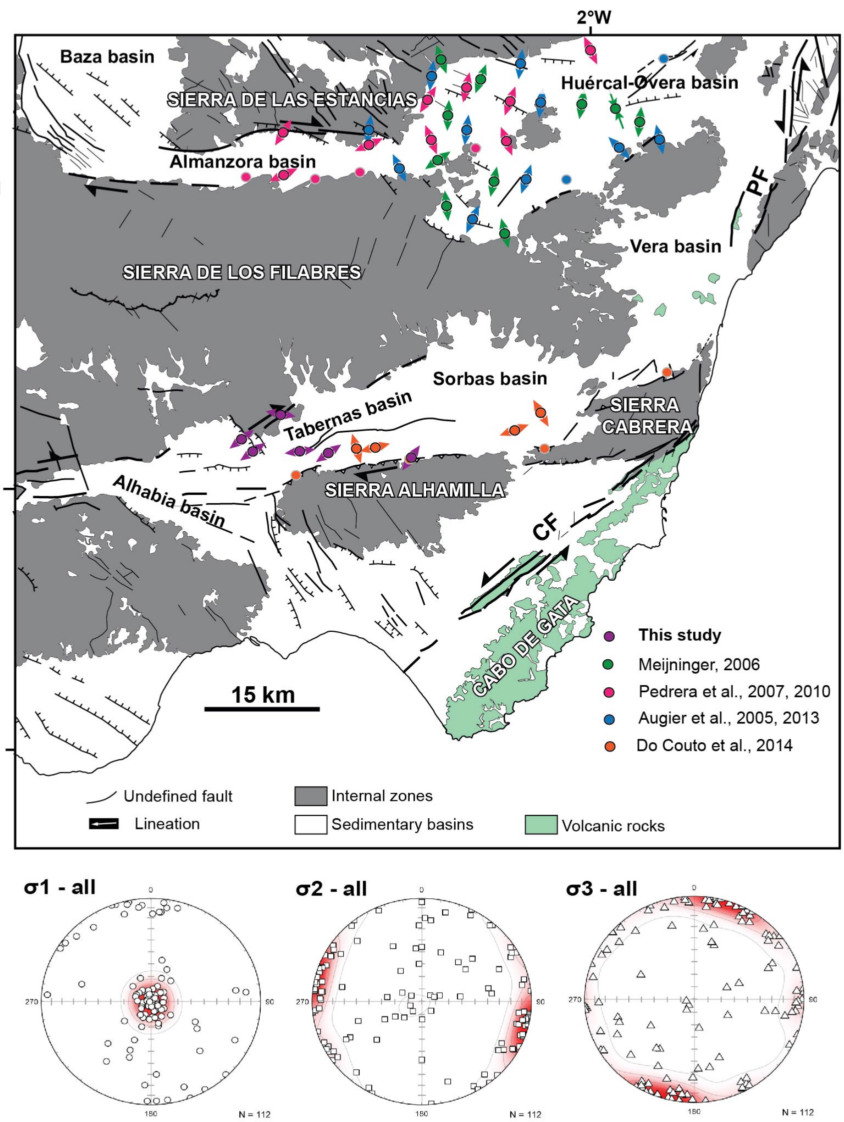

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Figure 8: Synthesis of stress regimes resolved from fault slip data inversion in Tortonian basins. Color-coded circles with arrows depict tectonic sites where extension (given as arrows) is horizontal (pure extensional or strike-slip stress regimes). Sites where reverse tectonic regimes prevail are shown as circles highlighted in grey. Below, stereoplots of paleostresses σ1, σ2 and σ3 show a compilation of all brittle tectonic regimes extracted from Table S1. Collectively they define a prominent extension oriented NNE-SSW with a subbordinate E-W-striking extension. CF: Carboneras Fault; PF : Palomeras Fault.

4.1 EW-directed faulting: evidence for pre-Tortonian oblique extension ?

In Tortonian intramontane basins, one of the main set of faults is represented by E-W-directed faults, including ENE-WSW to ESE-WNW sets. North of the Alpujarras Corridor (AC), 3 km to the NE of Canjáyar, the contact between the basal Tortonian conglomerates and the series of Alpujarride complex is exposed in the Rambla de Tices. It is shaped by a 2-meter thick fault zone (**Figs. 9a,b**) striking N100°E, which has a normal sense of slip with a right-lateral strike-slip component (**Fig. 9c**). It consists of cataclastic breccias and sheared blocks (boudins) of the host rocks (**Fig. 9d**). This major fault is found along the 65 km-long Alpujarras fault zone described by Martínez-Martínez (2006) as a major strike-slip dextral transfer zone south of the Sierra Nevada that acommodates both WSW-extension and dextral movement. It is mechanically consistent with NE-SW/ENE-WSW extension under a strike-slip regime as resolved nearby along the same faults system (Martínez-Martínez, 2006). **Fig. 9** indicates the fault is parallel to the basal Tortonian series but cuts across the Alpujarride complex. In the HOB, on the southern flank of the Sierra Limaria, the unconformity between the lower Tortonian red conglomerates and the Alpujarride units (Rambla de Cordoba, 2km NW Arboleas, **Figs. S1a, b**) is found reactivated as a normal fault with a dextral shear component.

To the North of TB, a large morphological surface presents a rare exposure of the micaschist basement of the Nevado-Filabrides complex allowing the study of deformation on the southern flank of the Sierra de los Filabres (**Fig. 10**). The deformed NF series shapes a kilometric-size antiform with axial planar surface dipping towards the North. The steeply-dipping cleavages directed NE-SW on its southern flank are deformed by numerous dextral shear zones with lengths ranging from 100 m to less than 5 m (**Fig. 10b, c**). In addition to isoclinal folds parallel to the main foliation that are clearly associated to an early stage of ductile EW-stretching, we recognize close to the strike-slip shear zones, steeply-dipping metric-size open to tight folds inclined to the NE (**Fig. 10d**). To the south, Tortonian conglomerates are overlying unconformably the folded NF foliation. This stratigraphic relationships and the average low dip of Tortonian strata (20°SE) indicate that strike-slip deformation occurred before the deposition of Tortonian conglomerates and after the tilting of the NF foliation (see cross section in **Fig. 10a**). This argues that the transition from W-directed ductile extension in the metamorphic domes known to have started in the Burdigalian and the right-lateral strike-slip faulting occurred around the Langhian-Serravallian (13-14 Ma). This interval is often considered to mark the transition from ductile to brittle extension (e.g. Augier et al., 2013). Because strike-slip faulting postdates folding of the NF foliation, and are consistent with WSW-ENE oblique extension, we suggest that the Sierra de los Filabres metamorphic dome formed in a transtensional strain regime. This hypothesis conforms with prediction of transtension at the tip of the STEP fault (Le Pourhiet et al., 2012) and with model of oblique extension (see **Fig. 3**).

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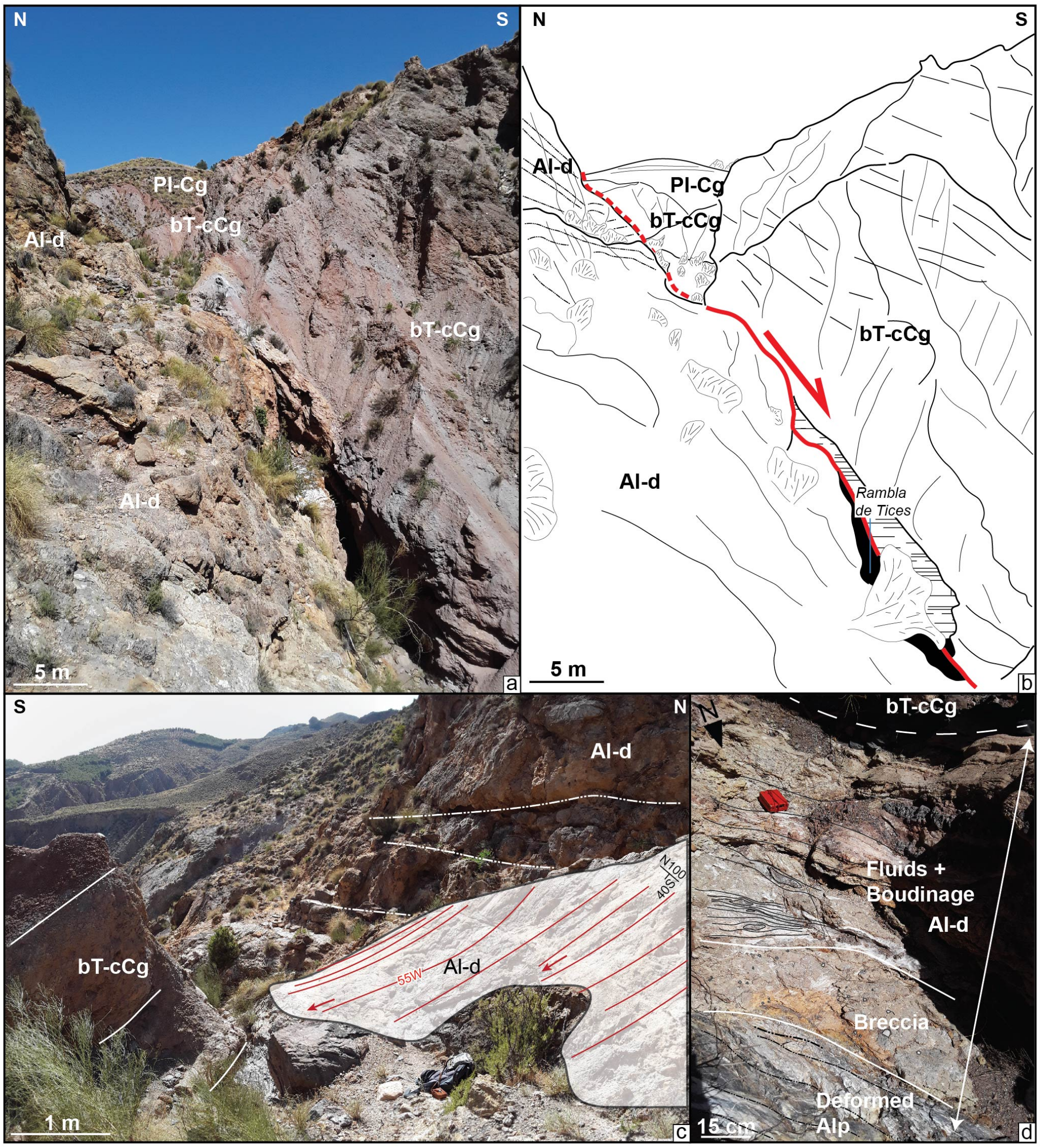

Figure 9. (a) and (b) Fault zone at the contact between the Tortonian basal conglomerates and the series of the Alpujarride complex south of AC (Rambla de Tices, see **Fig. 5** for location). (c) slikenslides on the fault zone reveasl a normal sense of slip with right-lateral strike-slip component found in association with (d) cataclastic breccias, sheared boudins of metamorphic and sedimentary rocks. Al-d: Alpujarride dolomites; bT-cCg: basal Tortonian continental Conglomerates; Pl-Cg: Pliocene Conglomerates. Coordinates 37.031944°N/-2.716274°E.

4.1.2. NW-SE-directed normal faulting

A second set is represented by NW-SE directed normal faults (**Fig. 8**). They are found, for instance, on the border of the NW-SE Alhabia basin, where they cut across the basement and interrupt the westward continuity of the Sierra de

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los Filabres. One major fault zone of this system is well exposed in the Arroyo del Verdelecho, 7 km to the west of Tabernas, on the eastern border of the Alhabia basin (**Figs. 11 and S2**). From a regional point of view this large NW-SE fault zone controls the deepening of the Tortonian basin and the position of Pliocene depocenter in its hangingwall, towards the West. NW-SE normal faults also cut across the lower Tortonian conglomerates in the hanginwall but their throw diminishes upward in the upper Tortonian margin sediments, suggesting fault activity during the late Tortonian (**Fig. 11**). One major fault zone is outlined by cataclastic breccias made of marbles originated from the exhumed Alpujarride complex in the Sierra de los Filabres (**Fig. S2**).

South of HOB (south of Arboleas), NW-SE faults are seen cutting through the late Tortonian sands and marls series, indicating that NE-SW extension is at least Tortonian (**Figs. S1c, d**).

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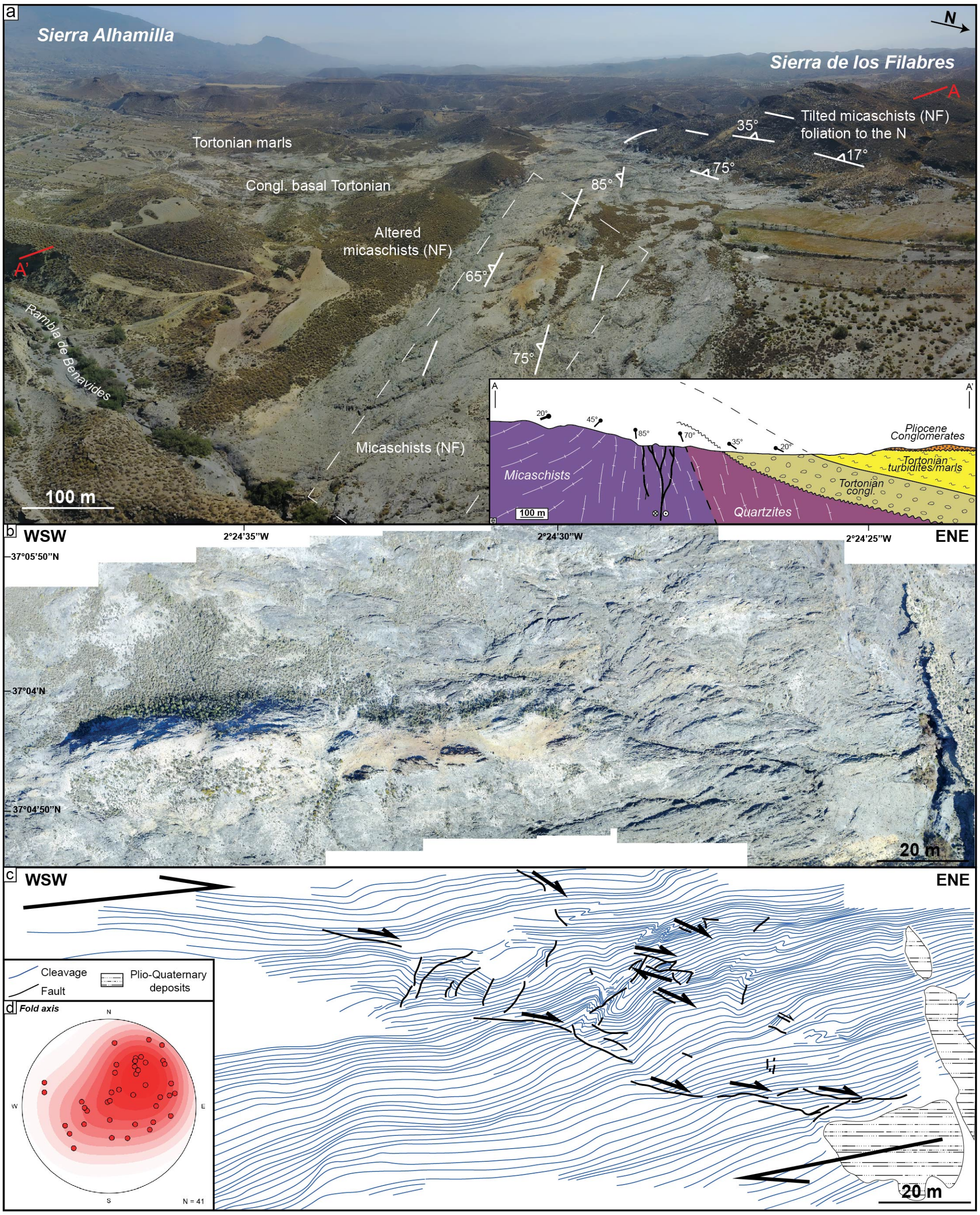

Figure 10 : (**a**) Drone view taken in the SSW direction of the southern flank of the Sierra de los Filabres at the contact with the Tabernas basin (see Figure 5 for location). Local folding of the micaschist is apparent in the right where the foliation is striking NNE-SSW and is dipping ~25°E whereas it is vertical and striking SW-NE in the center of the studied area forming paleosurface. Local cross section highlights the unconformable contact between the Tortonian conglomerates and overlying on the basement. (**b**) High-resolution drone images of the paleosurface and (**c**) line-

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drawing of the foliation revealing secondary folding (see (**d**) stereoplot of fold axes inclined to the NE) and dextral shear zones. Coordinates 37.082777°N/-2.410544°E.

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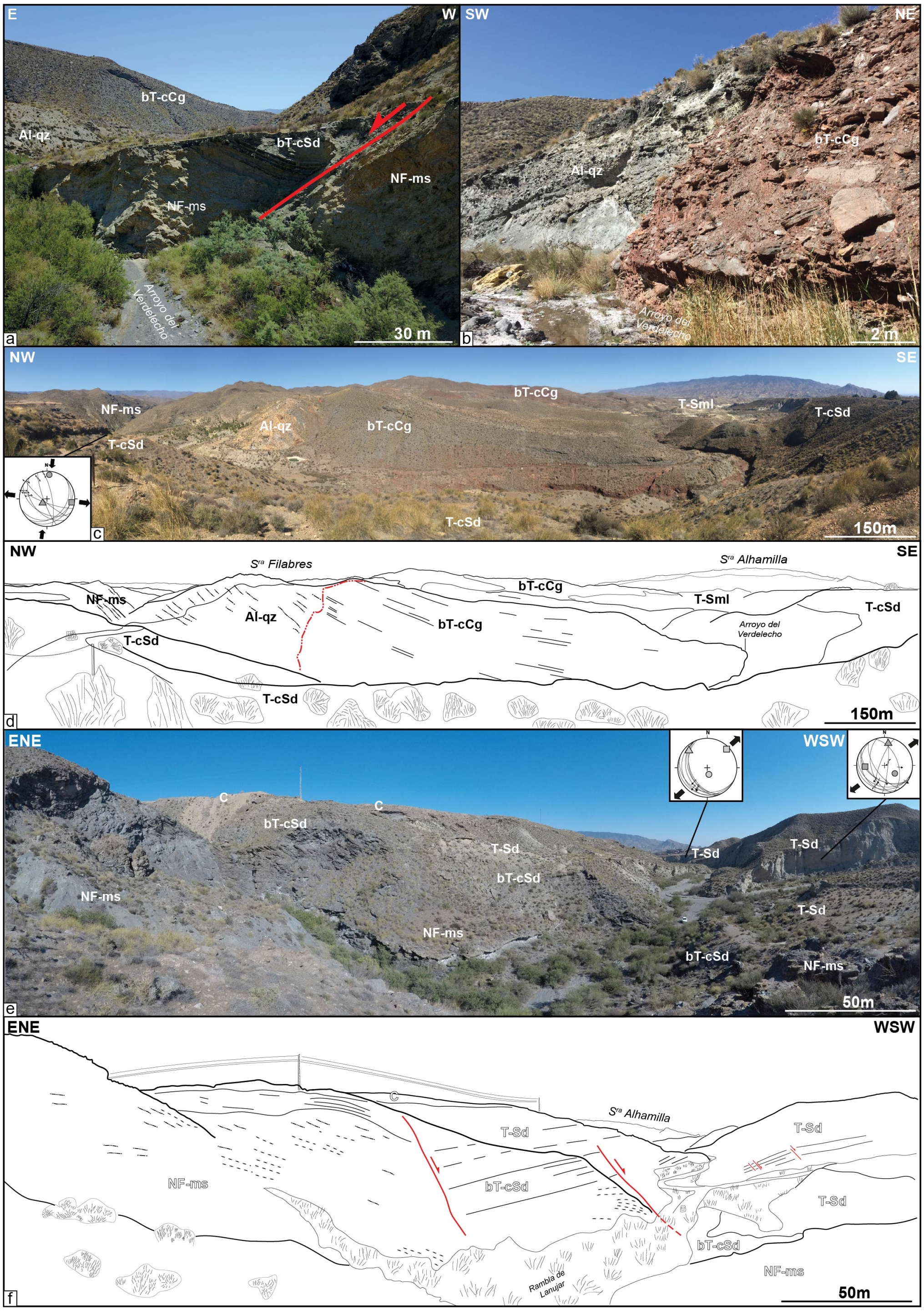

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Figure 11 : (**a**) Field photographs of a NW-SE normal fault at the contact between the Nevado-Filabride micaschists (footwall) and Tortonian sediments (hanginwall). (**b**) Stratigraphic contact between grey and red basal Tortonian continental conglomerates. These thick Tortonian series rest conformably on the Alpjuarride complex (**c**, **d**). Coordinates 37.059507°N/-2.478386°E. (**e, f**) NW-SE Normal faults cutting across the NF micaschists basement. These faults that also affetc the early Tortonian deposits are sealed by late Tortonian deposits and are therefore syn-depositional. See Figure 5 for location. Al-qz: Alpujarride quartzites; NF-ms: Nevado-Filabride micaschists; bT-cCg: basal Tortonian continental Conglomerates; bT-cSd: basal Tortonian continental Sandstones; T-cSd: Tortonian coarse Sandstones; T-Sd: Tortonian Sandstones; T-Sml: Tortonian Sandstones-marls; C: calcretes. Coordinates 37.061279°N/-2.490309°E. Paleostress orientations are in Table S1.

Both fault slip data and our own observations argue for a regional pre-Tortonian and syn-early Tortonian NNE-directed extension. This direction of extension is also found associated with less well-developed strike-slip regimes (**Fig. 8**). It is consistent with the D1-D2 phase of brittle deformation found in HOB (Augier et al., 2013). The fact that extension and strike-slip regimes occurred synchronously, or overlap rapidly in time, supports the view that they reflect the same large-scale tectonic setting. The reason why strike-slip faulting is less apparent in the field than expected in models in **Fig. 3** is likely to reflect the fact that oblique extension is not fully partitioned between normal and strike-slip components and is actually distributed along oblique structures. Moreoever, where strike-slip faults are found they are associated with narrow corridor basins or near the contact betwen the cover and basement but not in the center of HOB or TB. The NNE-SSW to NW-SE faults appear to postdate the deposition of the early Tortonian red conglomerates and is synchronous with the deposition of marine Tortonian series (**Fig. 12**). These normal faults currently form half-graben filled with Plio-Quaternary deposits (Guadix, Baza, Alhabia) and are active today. But the importance of extension-related brittle deformation over brittle compression decreases easttwards. Indeed, a late brittle compressional event oriented roughly N-S is described in the literature as a D3 brittle event (e.g. in HOB) associated with reverse and strike-slip faults (Augier et al., 2013). The post-late Tortonian shortening is seen responsible for fold amplification and reverse faulting on the northern limb of Sierra de Alhamilla and Sierra de los Filabres, and locally in the eastern part of the HOB near the termination of left-lateral strike-slip faulting evolution of the Alhama de Murcia fault (**Fig. 8**).

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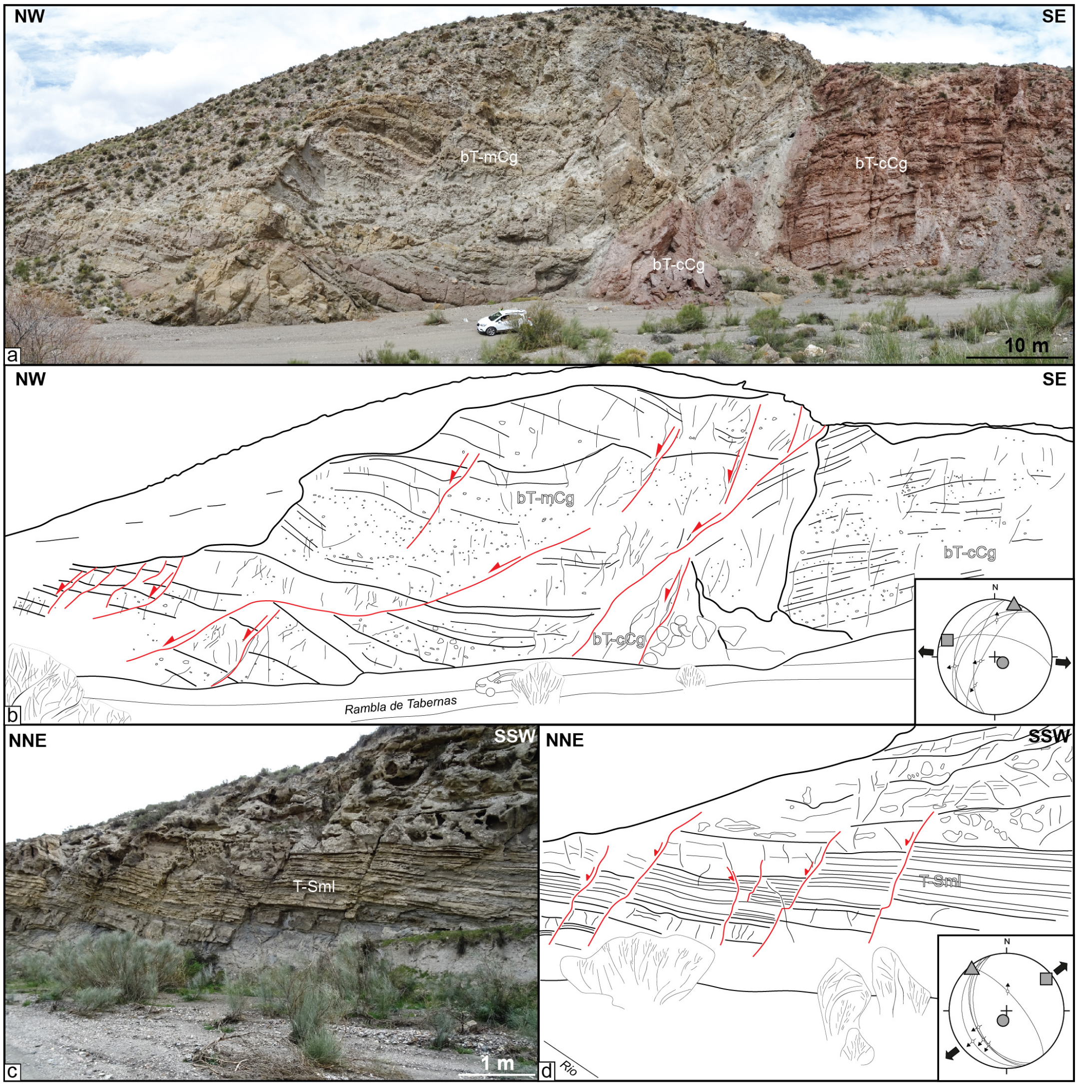

Figure 12: (**a, b**) N-S to NNE-SSW-oriented normal to dextral faults affecting the basal Tortonian continental conglomerates (bT-cCg) and marine conglomerates (bT-mCg) (Rambla de Tabernas). They form a long and tight E-W anticlinal crosses the Tabernas basin (see Figure 5 for location). (**c, d**) Several normal faults observed in Tortonian sandstones and marls (T-Sml). They are mostly oriented NNW-SSE. Coordinates 37.041648°N/-2.399318°E. Paleostress orientations are in Table S1.

5. N-S crustal-scale section across the oblique/transform margin of Alboran basin

To examine further the structural relationships between extension and strike-slip faulting across the Alboran margin, we explore 2D multichannel seismic lines acquired during the MARSIBAL 1-06 cruise (Comas and MARSIBAL1-06 Scientific Party, 2007) and ESCI cruises (Comas et al., 1995) across the Eastern Alboran basin (EAB). The studied seismic dataset consists of ~300 km and are deep-penetration multichannel seismic reflection studies (12 s two-way travel time - TWTT). Here, we study two lines namely MSB08 and MSB07 (see location in **Fig. 1**). For stratigraphic

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and structural correlations between the studied seismic lines, we used the Andalucia-A1 well (**Fig. 6a**) and results from ODP 977 and 978 legs (see location in **Fig. 1**). MSB08 is striking N70°E, slightly oblique to the shoreline. It is close, and runs parallel, to TM08 line of (Peña et al., 2018). It is calibrated by Andalucia-A1 well and ESCI-Alb1 line (Comas et al., 1995). Line MSB07 stretches in the N-S direction between the EAB in Spain and SAB to the north of Morocco parallel to line TM09 (Peña et al., 2018) and crosscusts line ESCI Alb2b presented in Comas et al. (1995) and Booth-Rea et al. (2007) (**Fig. 1**).

5.1 Offshore structures and stratigraphic architecture

The Carboneras Fault is well imaged north of MSB07 (**Fig. 13**). It forms a positive crustal-scale antiformal flower structure related to left-lateral strike-slip faulting that involves a Moho depth variation between 12 s to 9-8 s TWT after Gomez de la Peña et al. (2018). It separates a thin continental crust to the North (25-20 km; **Fig. 2**), from the magmatic calc-alkaline arc crust of the EAB with a thickness of 18 km in the south (Booth-Rea et al., 2007, 2018; Gomez de la Peña et al., 2018, 2020a).

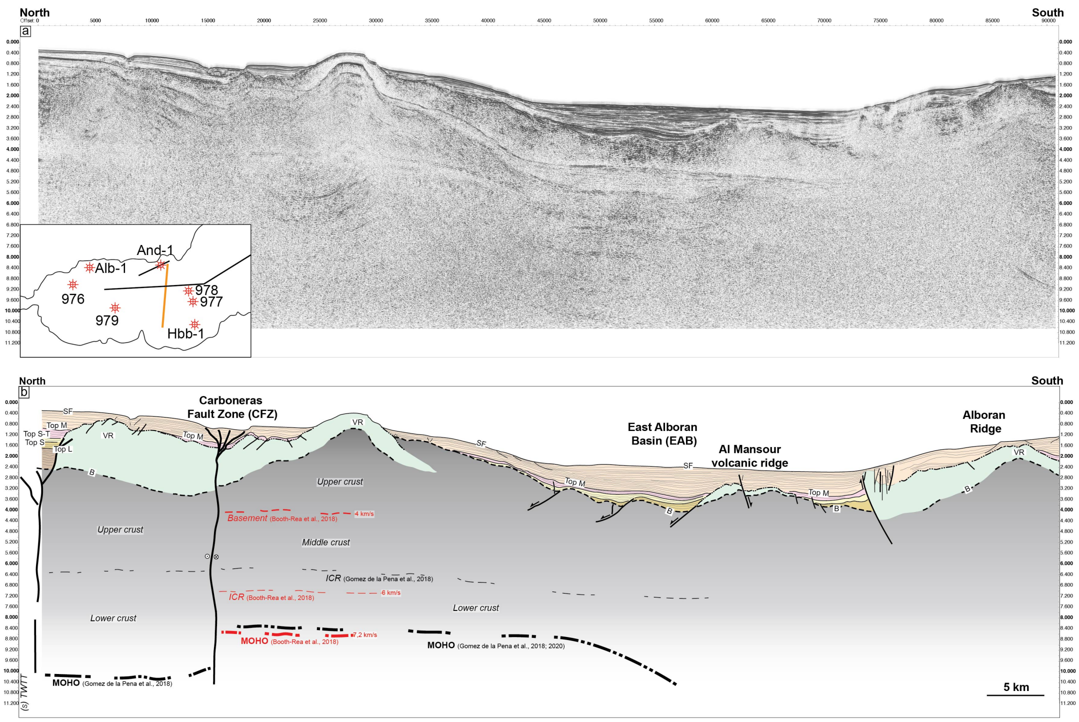

Figure 13 : Seismic reflection line MSB07 (location on **Fig. 1**). Discontinuous intracrustal reflectors (ICR) imaged between 3 and 6.5 s TWT, have been interpreted as mylonitic zones within the metamorphic basement (Carbonell et al., 1998; García-Dueñas et al., 1994; Gomez de la Peña et al., 2018). VR: Volcanic Ridge; B: Acoustic basement; Top L : Top Langian; Top S: Top Serravallian; Top S-T: top Serravallian-Tortonian; Top M: Top Messinian; SF: Seafloor.

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Reflection seismic data (**Figs. 13, 14, 15**) collectively show a relatively well stratified crust, corresponding to the sediment cover, down to 2.4-4 s TWT which outlines the acoustic basement with high reflectivity (B). Locally, the top basement reflector coincides with erosional palaeo-relief or high angle normal faults bounding basement highs. These faults are oriented mostly NW-SE to NE-SW and cut across the basement. We recognized on seismic images magmatic additions in the continental crust that are shaped by volcanic edifices exposed on the seafloor (e.g. Chella Bank) or slightly buried (Alboran Ridge) outlined by symmetric downlaps and onlaps of sediments. These constructions form topographic highs such as the Chella Bank on the MSB08 line (**Fig. 14**), the Alboran Ridge on the MSB07 line (**Fig. 13**) and the Maimonides Ridge on the ESCI-Alb2b line (**Fig. 15**). All the reflectors corresponding to layers as old as Tortonian are onlapping against the volcanic ridges confirming that the volcanic activity occurred during the middle to late Miocene times, which is otherwise shown by Duggen et al. (2008). Some reflectors up to the top Messinian (top M) onlap onto the volcanic ridges probably as a result of Pliocene uplift.

The stratigraphy offshore, on the continental crustal domain, is defined by the recognition of five seismic stratigraphic units in Andalucía-A1 well (Jurado and Comas, 1992) labeled I-V from top to base (**Figs 6** and **16**) and separated by unconformities. The seismostratigraphic units I to V vary in thickness **(Fig. 16**) and their architecture is conditioned by the occurrence of basement highs and crustal-scale faults.

Below the Miocene sedimentary filling, Andalucia-A1 well reveals ~190m of phyllitic and quartzitic meta-sediments (2.4 to 4 s TWT below the Alboran basin, **Figs. 13** and **14**) topped by Langhian to Tortonian marls (top at ~1.6 to 3.4 s TWT below the Alboran basin) interbedded with Tortonian-Messinian tuffs and basaltic lavas. These units have been correlated in the magmatic arc crust of EAB after Gomez de la Peña et al. (2020b). The older deposits (Unit V) Langhian-Serravallian in age, consist of clays and marls with intercalated sands and volcano-clastic deposits. The seismic facies of this Unit V is made of moderate amplitude and low frequency discontinuous reflections packages (Figure 18), and is only present in the Northern Alboran Basin. They are correlated with volcanic series in the EAB (vY3) (Gomez de la Peña et al., 2020b). They pass upward into Serravallian sand-silty clay turbidite (Unit IV) possibly correlated with volcanic series in EAB (vY2 after Gomez de la Peña et al., 2020b). This unit exhibiting low to moderate amplitude, moderate frequency drawing continuous sheeted to disrupted reflectors, is unconformably overlying Unit V and locally onlaps onto the basement. Thickness of Unit IV remains rather thin in the North and East Alboran Basin. It can’t be properly identified in the South Balearic Basin, east of the Maimonides volcanic ridge (**Fig. 15**). The Unit III dated from late Serravallian to late Tortonian is represented by sandstones interbedded with volcano-clastic levels whih correlates in EAB with volanics vY1 unit. Unit III contains internal reflections characterized by low to moderate amplitude, moderate frequency continuous sheeted reflectors. Its thickness remains relatively constant from the NAB to the EAB, and is identified beneath the Messinian Unit II in the South Balearic Basin. Unit II corresponds to the Messinian evaporite, carbonate, volcanic, and volcaniclastic deposits interbedded with fine-grained sediments and is equivalent to unit III of (Peña et al., 2020b) in EAB. Seismic facies of Unit II is marked in the Alboran domain by lower amplitudes and lower frequency reflectors. In ESCI-Alb2b line, Unit II increases drastically east of the Maimonides ridge, which delimits the western boundary of the salt deposits in the Western Mediterranean basin during the Messinian Salinity Crisis (Haq et al., 2020). Unit II is topped by Unit I made of Pliocene to Quaternary clays and

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sanstones, which are correlated with units II and I in EAB (Gomez de la Peña et al., 2020b). Unit I is marked by thinly bedded, mostly parallel, high-frequency and low amplitudes reflectors (**Fig. 18**). Its thickness fluctuates in response to sedimentary processes (Juan et al., 2016).

Along line MSB08 (**Fig. 14**) the Langhian-Serravallian (Unit V) is maximum 1600 m-thick (using a P-wave velocity of 3.2 km/s calculated within Andalucia-A1 well. In EAB, south of Carboneras Fault Zone, the total thickness of Unit V is only ~300 m on MSB07 (**Fig. 13**) and is absent in ESCI-Alb2b (**Fig. 15**). The Serravallian-Tortonian (Unit IV-III) interval shows only very limited sediment accumulation (~300 m) except near the NW-SE oriented normal faults where growth geometries are visible. These normal faults are sealed by the Tortonian-Messinian deposits, indicating a syn-sedimentary faulting during the middle Miocene (**Fig. 13**). With respect to offshore observations this sedimentary infill is more continuous and is also much thinner conpared to TB and HOB where they are represented by thick conglomerates and marls/turbidites (> 1km) (**Fig. 7**), and they are eroded or not deposited along the axes of the metamorphic domes. The Messinian deposits (Unit II) are ~150-350 m-thick north of CF (MSB07-08 ; **Figs. 13, 14**) and increase to about 1200 m eastward in the eastern EAB (ESCI-Alb2b ; **Fig. 15**), and in Algero-Balearic basin (Gomez de la Peña et al., 2020b). The top Messinian reflector is topped by thick horizontal sedimentary strata, with a maximum thickness of 1.2 s TWT (~2.4 km assuming a velocity of 2 km/s) on line MSB07, suggesting an important channel system during the Pliocene.

The Pliocene-to-Quaternary series are poorly deformed except in the vicinity of CF and near the Alboran Ridge where this is associated with south-dipping reverse fault (**Fig. 13**). This late and still active compressional tectonics is revealed by the overthrusting of the SAB over the south margin of the EAB e.g. (Martínez-García et al., 2011).

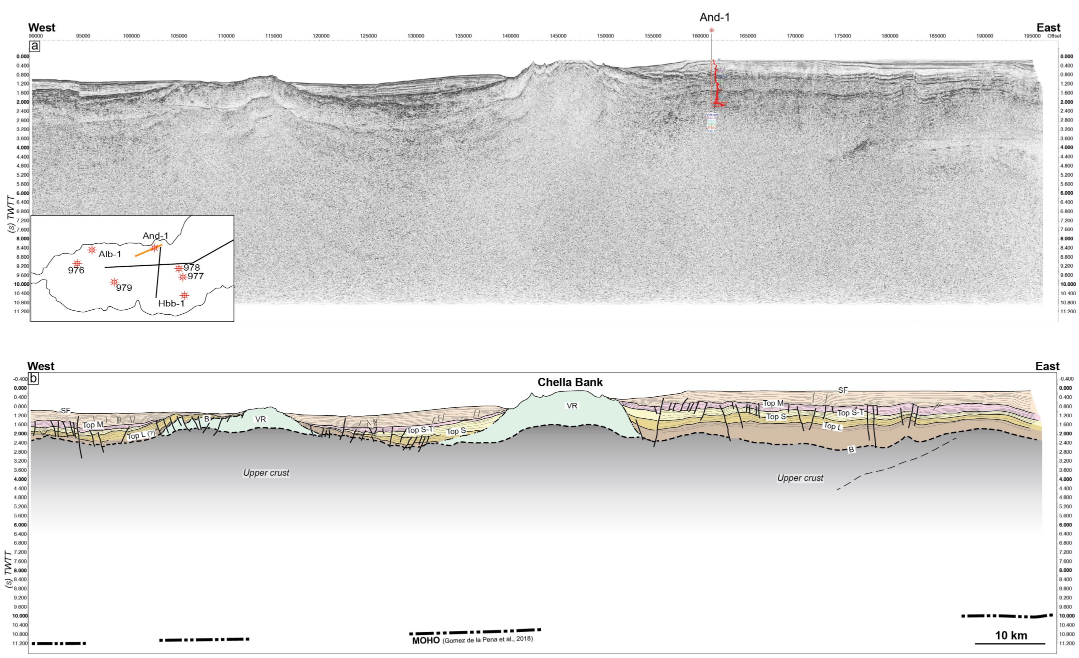

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Figure 14 : Seismic reflection line MSB08 (see location on **Fig. 1**). See Figure 13 for abbreviations. See also Figure S3 showing a zoom on the main seismic facies recognized in Andalucia-A1 well.

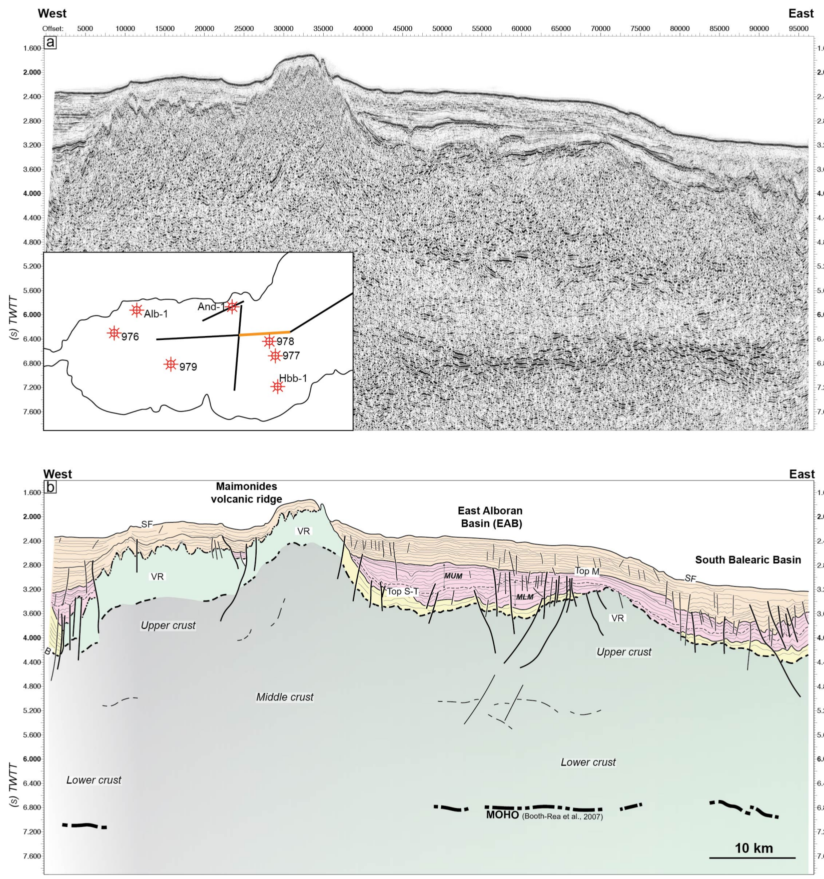

Figure 15. (**a, b**) Seismic reflection line ESCI-Alb2b and intepretation (see Figure 1 for location). Seismic units are correlated with those defined by Booth-Rea et al. (2007). See Figure 13 for abbreviations.

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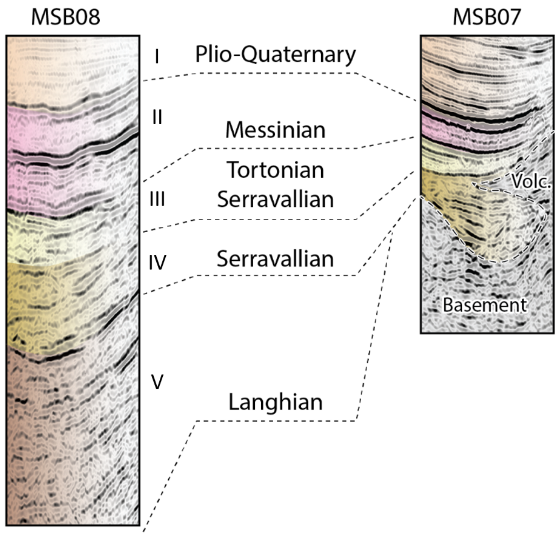

Figure 16 : Seismic facies of units I to V seen through seismic lines MSB08 close to the shoreline and the line MSB07, located deeper in the East Alboran Basin.

5.2 N-S crustal cross-section of the Alboran margin accounting for strike-slip faulting

Based on subsurface constraints and field data, we have built a crustal cross-section across the rifted margin from the Sierra de las Estancias and Huercal-Overa basin (HOB), which represents the proximal margin, to the center of the Alboran margin (**Fig. 17**). The proximal margin is defined by a 30-35 km-thick crust. It preserves part of the thickness acquired during former orogenic phase that has been little involved in crustal thinning. The onset of crustal thinning to the south is recorded by the formation of strongly subsident and asymmetric basins of the HOB and TB, shaping the upper neck domain. This domain is characterized by orthogonal and oblique extension during the Tortonian accommodated by normal and strike-slip faulting. This boundary also corresponds to the position of the major STEP fault documented by seismology. From the Sierra de los Filabres to the south, the crustal thickness reduces to 25 km in the Tabernas basin along the Alpujarras strike-slip corridor and below the Sierra Alhamilla. The Nijar basin depicts the transition towards offshore distal domains with a crustal thickness of 20 km. The Tortonian and Messinian marine sediments are also thicker and a number of volcanic bodies accompany crustal thinning. Crustal thinning appears localized along the Carboneras Fault (CF), which juxtaposed crust with different crustal thickness (**Fig. 19**). South of CF, the crust thickness reduces below 20 km and shows increasing magmatic additions making the magmatic arc crust of the EAB (Gomez de la Peña et al., 2018 ; 2020). Interestingly, normal faulting in the EAB is sealed by middle-upper Tortonian deposits. Crustal deformation then shifted to the north in the CF and EBSZ strike-slip fault zones and to the south along the Alboran Ridge where reverse faulting occurred.

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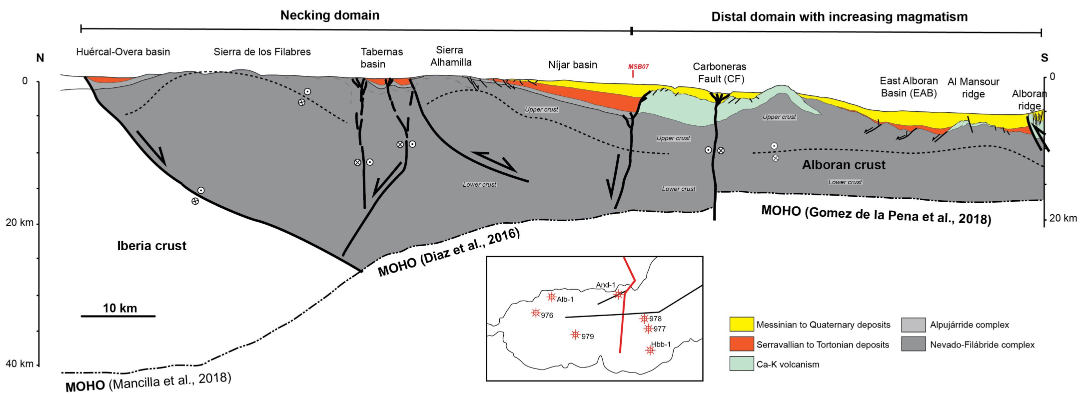

Figure 17. Crustal-scale cross section of the Alboran margin in the eastern Betics interpreted based on onshore and offshore contraints presented in the text. Note that in the necking domain the extension of faults downwards to Moho depths is not imaged on the seismics and therefore largely inspired by inferences from 3D numerical models (see Fig. 3).

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7. Implications

The question of whether the Miocene tectonic evolution of the Betics reflects crustal thinning associated with oblique back-arc rifting as suggested from present-day strain patterns is unclear in the literature. Back-arc extension, recent tectonic inversion and STEP faulting are generally considered to result from separated processes. We found based on a comparison between numerical models and analyses of basin evolution, fault kinematics and structure of the margin in the eastern Betics compelling evidences that crustal thinning occurred under oblique extension and was not restricted to the post-Tortonian evolution. Rather, oblique rifting possibly operated since at least the middle Miocene, as the slab retreat started in the Alboran basin and is therefore kinematically associated with STEP faulting.

One of the most striking tectonic feature of the Alboran margin (**Fig. 17**) is the abrupt N-S crustal thinning, from 35-30 km to 25-20 km, oblique to the direction of slab retreat. The history of sediment infill and rates of subsidence in intramontane basins (**Figs. 6 and 7**) combined with the analyses of fault slip data, confirm that brittle extension oriented from N20°E to EW occurred during an interval spanning from the Serravallian-early Tortonian to the late Tortonian (14-8 Ma). This extension is found associated with both normal and strike-slip regimes. In more details, these data suggest that N20°E extension is more represented in HOB, while the ENE-WSW to EW extension is found related with the evolution of the Almanzora corridor, Alpujarras corridor and Tarbenas basin flanking the metamorphic domes (**Table S1**). There are additional evidence that EW-directed dextral strike-slip faulting did occur during the Tortonian to the South and West of the HOB and represents this main phase of basin subsidence. These large-scale faults are later cut by Tortonian NW-SE faults that argue for more recent EW extension. Therefore, we infer that the domain south of the HOB, which also corresponds to a thinnest crust, has experienced transtensional deformation and EW extension.

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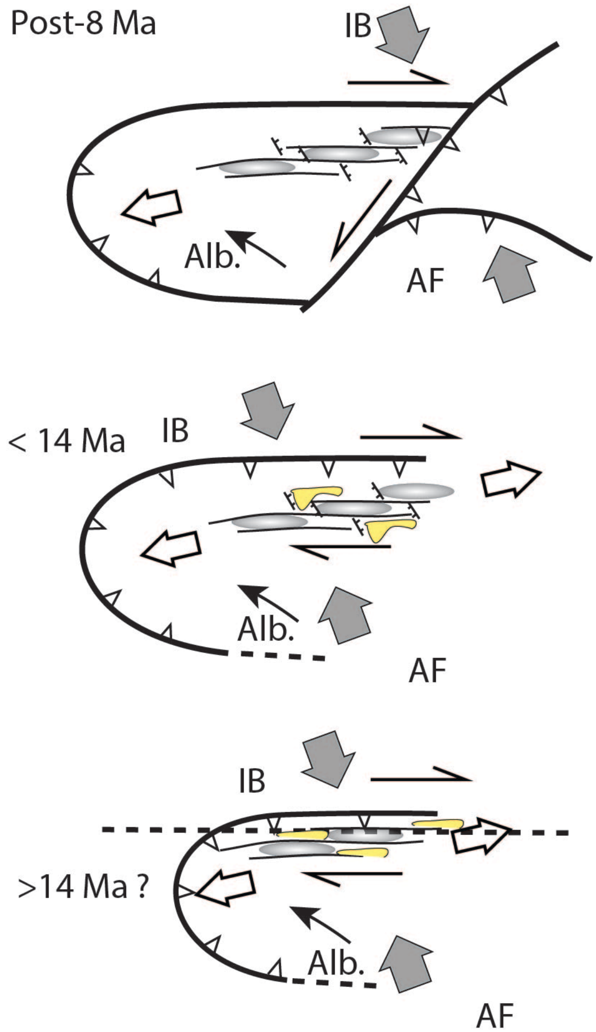

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555 **Figure 18**: Tectonic model of the evolution of the northern margin of the Alboran Rift. Large grey and white double
556 arrows depict shortening, which is parallel to the AF/IB convergence, and the highly oblique extension, respectively.
557 The thin black arrows is showing the motion of Alboran relative to Iberia (IB) taken from Figure 4. Half arrows
558 depicts the distributed strike-slip faulting in the Betics. NW-SE directed normal fault and strike-slip basins (yellow)
559 are consistent with the oblique extension. Grey-shaded ellipses represent the metamorphic domes.
560
561 Several key specific tectonic features found in the eastern Betics are predicted by 3D models of oblique extension
562 (**Figure 3**). Those include the E-W trending faults that are prevalent on the upper neck domain (i.e. Sierra de las
563 Estancias and HOB), and E-W strike-slip faults (Almanzora and Alpujarras corridor) and NW-SE normal faults that
564 are found associated with more distal domains where crustal thinning is the highest. Brittle E-W-directed stretching
565 and dextral transcurrent deformation started in the Langhian-Serravallian (14-13 Ma). Tectonic inversion seems, in
566 contrast, to have been increasingly more important when approaching the Carboneras and Palomeras strike-slip faults
567 in the East since the late Tortonian.

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According to temporal constraints, ductile thinning may have occurred between 23 to 16 Ma prior to brittle faulting at 14-13 Ma (**Figure 18**). The late/post-Tortonian times marks a change in the tectonic evolution of the region (Jolivet et al., 2021a; Mouthereau et al., 2021; Rat et al., 2022) as the mantle slab eventually detached and is responsible for Ca-K magmatism at 11-7 Ma (Duggen et al., 2008, 2004), compression and tightening of the metamorphic domes associated with the formation of the the EBSZ.

The strike-slip deformation model has the advantage to explain N-S crustal thinning in the Betics while back-arc extension is oriented E-W, in a continuum of deformation from the Miocene to the present. In this model, ductile stretching and ductile detachment associated with the development of the domes are the expression of oblique E-W extension. This provides a coherent scheme linking the formation of EW-directed basins in the brittle field associated with strike-slip faulting, and NW-SE/NNW-SSE sedimentary basins (Guadix, Baza, Alhabia) formed in transtension during the Tortonian. As such, the oblique extension, which is closely associated with STEP faulting required by slab retreat, is overall a characteristic feature of the regional NW-SE/NNW-SSE convergence since at least the Miocene. Only recently, around 8 Ma, as the slab detached, shortening started to prevail in the vicinity of the EBSZ (**Figure 18**). As convergence was under way during oblique back-arc extension, high-pressure metamorphism and subduction possibly occurred during the mid-Miocene as argued in eastern Betics (Platt et al., 2013). Moreover, the case of exhumation of high-pressure rocks in oblique convergence setting associated with near-parallel orogeni extension is documented in other active orogen like Taiwan (Conand et al., 2020).

This highly oblique northern Alboran margin differs from typical transform fault margin such as those associated with the Altantic ocean because it accommodates variations in intra-plate extensional movements, triggered by slab roll-back not variations in spreading rates. Strike-slip faults may have originated as low-angle normal which were later reactivated as thrusts during margin inversion. Similar observations, including metamorphism, strike-slip faulting, high geothermal gradients and volcanism has been made in Seram, north of the Banda Arc, which represents an other example of extremely thinned crust formed perpendicular to the direction of the slab retreat (Pownall et al., 2013). Such a narrow rifted margin associated with lithospheric STEP fault defines a class of oblique (and transform) margin that is expected to be hardly preserved in the geological record due the transient nature of retreating subduction systems.

Data availability.This study is based on data compilation. Data used in this study can be found in the appropriate references. Paleostress tensors obtained by the inversion of fault slip data are available online in the Supplement.

Supplement.The supplement related to this article is available on-line at:

Competing interests.The authors declare that they have no conflictof interest.

Authors contribution

ML and FM, conceptualize, prepared figures and tables, compiled and interpreted field structural data and wrote the paper. DC provided and interpreted the seismic lines, reviewed the text and contributed to the writing. AJ carefully

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exmined the implementation of his numerical results and reviewed the text. EM, SC and VM, supervised and coordinate the different project tasks and reviewed the text.

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