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# Late extension of a passive margin coeval with subduction of the adjacent slab: The Western Alps and Maghrebides files

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**Abstract** – The evolution of the Alpine Tethys margins during the beginning of the African-Eurasian convergence was little studied compared to their evolution during the post-Pangea rifting and oceanic expansion, *i.e.*, from the Early Jurassic to the early Late Cretaceous. The present work firstly aims to make up for this shortcoming in the case of the distal European margin of the Alpine Tethys, namely the Briançonnais domain of the Western Alps. We show that this margin was affected by strong post-rifting extension mainly in Late Cretaceous-Paleocene times and propose to make it the type of the (rare) "Late Extension Passive Margins". Remarkably, this extension shortly preceded Lutetian times, when Briançonnais margin encroached the SE-dipping subduction zone under the Adria microplate. Secondly, we assess the post-rifting evolution of the north-Tethyan paleomargin in the Maghrebides transects, *i.e.*, south-west of the Briançonnais transect along the same European-Iberian paleomargin. For this purpose, we consider the Triassic-Eocene series of the "Dorsale Calcaire" in the Alkapeca Blocks located along southeastern Iberia until the Eocene then transported onto the North African margin. Examination of the literature shows that the Tethyan margin of the Alboran block was strongly affected by normal faulting as early as Late Jurassic-Early Cretaceous times whereas post-rifting extension of the Kabylian blocks mainly occurred in the Late Cretaceous-Paleocene like in the Briançonnais. We propose that post-rifting extension of the Alboran block southern margin resulted from the sinistral movement of Africa relative to Iberia while the later extension of the Kabylian blocks can be related to the further convergence kinematics. Subduction of the Ligurian-Maghrebian slab under the North African margin would have occurred at that time in the southward continuation of the Alpine subduction. The overriding Adria and North African margins did not experience significant compression at that time. During the Eocene, a subduction polarity reversal occurred, which was associated with the relocation of the subduction zone along the Alkapeca block. This was the beginning of the Apenninic subduction, which triggered the back-arc opening of the Mediterranean basins.

**Keywords:** Rifting / Extension / Subduction Polarity Reversal / Western Alps / Tethys / Late Cretaceous

**Résumé – Extension tardive d'une marge passive contemporaine de la subduction du slab adjacent : les dossiers briançonnais et maghrébins.** L'évolution des marges de la Téthys alpine pendant le début de la convergence Afrique-Eurasie au Crétacé supérieur a été peu étudiée par rapport à leur évolution du Lias au Crétacé inférieur, pendant le rifting post-Pangéen et l'expansion océanique. L'objectif du présent travail est en premier lieu de pallier cette lacune dans le cas du Briançonnais, marge européenne distale de la Téthys alpine. Nous montrons que cette marge a été le siège d'une forte extension au Crétacé supérieur-Paléocène et proposons d'en faire le type des rares « Marges Passives à Extension Tardive ». Fait remarquable, cette extension tardive est contemporaine de la subduction de la croûte téthysienne sous la microplaque Adria, le Briançonnais entrant lui-même dans la zone de subduction dès le Lutétien. En second lieu, nous revisitons l'évolution de la bordure nord-téthysienne sur plusieurs transects des Maghrébides, au sud-ouest du transect Briançonnais mais sur la même marge européenne. Nous considérons la série triasico-éocène de la "Dorsale Calcaire" dans les blocs Alkapeca riftés de la bordure sud-est d'Iberia puis transportés après l'Eocène sur la marge nord-africaine. L'examen de la littérature montre que la marge téthysienne du bloc d'Alboran a été

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fortement affectée par des failles normales dès la fin du Jurassique-début du Crétacé alors que l'extension post-rifting des blocs kabyles s'est principalement produite au Crétacé supérieur-Paléocène comme dans le Briançonnais. Nous proposons que l'extension post-rifting de la marge méridionale du bloc d'Alboran résulte du mouvement sénestre de l'Afrique par rapport à l'Ibérie, tandis que l'extension des blocs kabyles peut être liée à la cinématique ultérieure de convergence. La subduction de la plaque liguro-maghrébine sous la marge nord-africaine se serait produite à cette époque dans le prolongement sud de la subduction alpine. Les marges des plaques supérieures Adria et Africa n'ont pas subi de compression significative à cette époque. Au cours de l'Éocène, une inversion de la polarité de la subduction s'est produite, associée à la relocalisation de la zone de subduction le long du bloc Alkapeca. C'est le début de la subduction apenninique, responsable de l'ouverture arrière-arc des bassins méditerranéens.

**Mots clés :** Rifting / Extension / Inversion du pendage de subduction / Alpes occidentales / Téthys / Crétacé supérieur

## 1 Introduction

Extensional tectonics was intensely studied during the last decades in the Alpine belts from the Himalaya to the Alps, Pyrenees and Western Mediterranean belts. Extension occurred during various stages of the evolution of these subduction-collision belts, from the rifting (Manatschal and Müntener, 2009; Chenin *et al.*, 2017; Lagabrielle *et al.*, 2019; Motus *et al.*, 2022) to the impending collisional stages (Royden, 1993; Jolivet *et al.*, 2008; Molli, 2008; Van Hinsbergen *et al.*, 2014), and finally the post-collisional stages (Froitzheim *et al.*, 1997; Selverstone, 2005; Sue *et al.*, 2007; Jolivet *et al.*, 2020; Pye *et al.*, 2022). It is well known that during subduction at the active margin, extension may affect the back-arc domain (Fig. 1A). This is illustrated by classical peri-Pacific examples such as the Okinawa trough (Sibuet *et al.*, 1987; Fabbri and Fournier, 1999), Mariana Trough (Oakley *et al.*, 2008) and Lau basin (Bevis *et al.*, 1995) exemplified by the opening of the Mediterranean basins due to the Hellenic (Jolivet and Faccenna, 2000; Brun *et al.*, 2016) and Apenninic (Lonergan and White, 1997; Van Hinsbergen *et al.*, 2014; Leprêtre *et al.*, 2018) subduction roll-back during Late Eocene-Miocene times. Instead, examples of syn-subduction, renewed extension at the passive margin (Fig. 1B) are scarce in the global literature, seemingly concentrated in the Central Mediterranean area (Fig. 2) where it is described in the Pelagian-Sirte basin (Capitanio *et al.*, 2009; Frizon de Lamotte *et al.*, 2011; Khomsi *et al.*, 2019), Central Apennines (Carminati *et al.*, 2014) and Briançonnais (Michard *et al.*, 2022). We will name hereafter this type of margin "Late Extension Passive Margin" (LEPM). Mechanisms at work in the late extension of a LEPM are likely, on the one hand, extensional stress at the extrados of the bending lithosphere (Capitanio *et al.*, 2007), and on the other hand, the slab pull, potentially increased by avalanching below the 600 km mantle discontinuity (Capitanio *et al.*, 2009). LEPMs should not be confused with passive margins affected by "re-rifting", a process considered by Bradley (2008) as the origin of ribbon-microcontinents, thus rather belonging to back-arc extension at active margins (*e.g.*, Avalonian-Cadomian microcontinents; Linnemann *et al.*, 2014). The active Taiwan orogenic system favorably compares with the Western Alps orogen (Molli and Malavieille, 2011), but rifting of the South China Sea passive margin occurred from the Albian to the Late Eocene, well before its Miocene subduction beneath the Taiwan accretionary prism (Conand *et al.*, 2020). According to Yu and Chou (2011), the Plio-Quaternary renewed extension occurred in the western Taiwan foreland basin due to forebulge mechanism. This mechanism, well-known in the Late Eocene-Oligocene basins of the External Alps (Sinclair, 1997), mostly results in an external-ward migrating uplift of the bending plate with minor extension. Thus, it cannot account for the late extension observed in a typical LEPM as the Briançonnais paleomargin (Michard *et al.*, 2022).

In the first part of the present review paper, we investigate a LEPM exemplary case study provided by the European magma-poor passive margin, inverted and now exposed in the Briançonnais domain of the Western Alps (Fig. 2). The Briançonnais paleomargin underwent a late extensional event, only briefly described so far (Michard *et al.* 2022), during the Late Cretaceous-Early Eocene Alpine subduction of the Alpine Tethys or Piemonte-Liguria oceanic lithosphere beneath the Adria microplate (Schmid *et al.*, 2017). Secondly, we consider the western equivalents of the Briançonnais units at the northern border of the Ligurian-Maghrebian Mesozoic Ocean, which continued the Alpine Tethys until its connection with the Central Atlantic (Rosenbaum *et al.*, 2002; Chalouan and Michard, 2004; Schettino and Turco, 2011; Leprêtre *et al.*, 2018). These Briançonnais equivalents are the Alboran-Kabylias-Peloritani-Calabria (AlKaPeKa or Alkapeca) terranes (Bouillin, 1986; Bouillin *et al.*, 1986) that make up the Internal zones of the Maghrebides Belt (Tell-Rif orogen) and crop out from the Moroccan Rif and Betic Cordilleras of Spain to the Peloritani Mountains of Sicily and Calabria in southern Apennines (Fig. 2). The Variscan basement of the Alkapeca terranes was part of south-eastern Iberia until the Early Jurassic opening of a narrow Betic Ocean (Puga *et al.*, 2011) or OCT domain (Jabaloy Sánchez *et al.*, 2019), a minor, poorly defined branch of the Ligurian-Maghrebian Tethys (Stampfli *et al.*, 2002). The Alkapeca domain was fragmented and carried onto the African and south-eastern Iberia margins during the Late Eocene-Oligocene opening of the back-arc Mediterranean basins. In other words, prior to the Late Eocene, the future Alkapeca terranes were located on the same European side of the Alpine Tethys as the Briançonnais. This led us to investigate whether a LEPM, Late Cretaceous-Paleocene extensional event can be recognized in the Alkapeca terranes. If so, such an extensional event could suggest a geodynamic setting similar to that of the Briançonnais, and then a Late Cretaceous-Paleocene, SE-dipping Alpine subduction of the

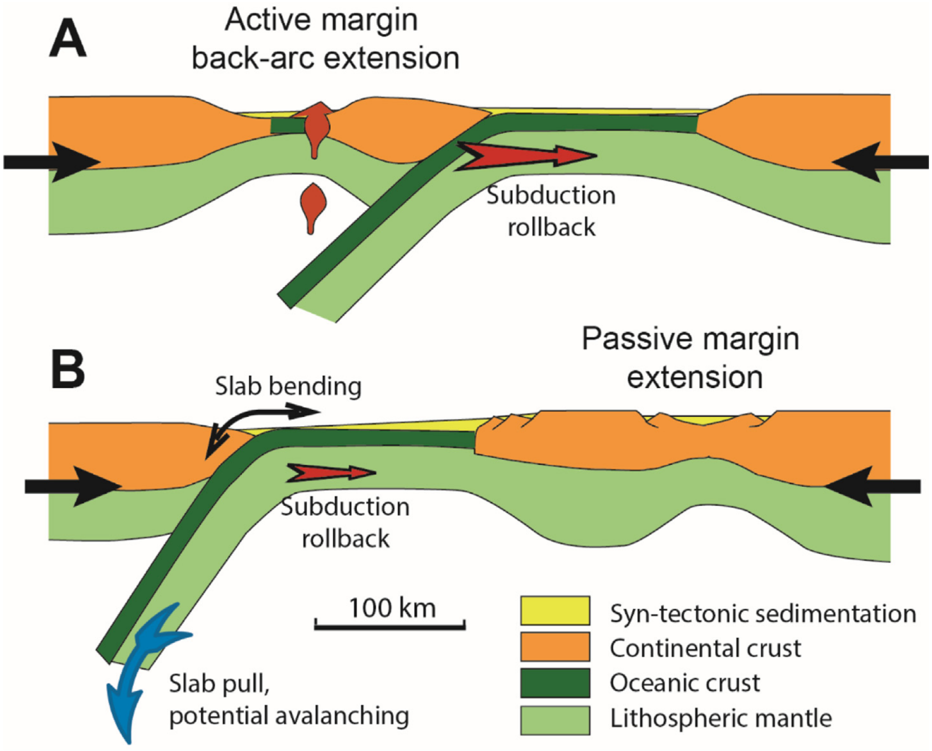


**Fig. 1.** End-members of syn-subduction extension settings coeval with plate convergence (large black arrows). A: Back-arc extension at active margin with subduction rollback (e.g., Western Mediterranean Tertiary basins, Aegean Sea). B: Renewed, late extension at passive margin related to lithospheric bending and slab pull and rollback (Sirte Cretaceous basin, Central Apennines, Briançonnais).

westernmost Tethyan lithosphere beneath the North-African paleomargin until the onset of the Apenninic subduction during the Eocene.

## 2 Briançonnais paleomargin

### 2.1 Structural setting

In the Western Alps curved belt (Fig. 3A, B), the classical Briançonnais nappes extend in the middle of the Internal (Penninic) metamorphic zones. To the west, the Briançonnais nappes overlie the Subbriançonnais-Valaisan units, and both of them are widely thrust onto the External zones (Helvetic, Dauphinois, Provençal zones), virtually devoid of Alpine (Cenozoic) metamorphism. On their eastern border, the Briançonnais nappes are back-folded / back-thrusted onto the ophiolitic "Schistes Lustrés" nappes that derive from the part of Alpine Tethys referred to as Piemonte-Liguria Ocean (Fig. 3C). This complicated geometry results from the latest stage of collisional deformation of the internal metamorphic prism that formed at the front of the subduction zone by the end of the subduction-exhumation processes when the ophiolitic units were thrust above the Briançonnais ones. The Acceglio half-window clearly illustrates the late back-folding event (Fig. 3B; Michard *et al.*, 2022 and references therein). The classical Briançonnais nappes and the Prepiemonte units detached from more internal parts of the Briançonnais terrane mainly consist of Mesozoic-Early Cenozoic series, but Carboniferous and Permian clastic and volcanic rocks are also found (Fig. 4). Only some slices of the Variscan basement from which these nappes became detached are exposed to the north of the Briançonnais nappes. In contrast, such basement makes up most of the so-called Internal Crystalline Massifs (ICM: Dora-Maira, Grand Paradis, Mont Rose). Thus, the Briançonnais domain *sensu lato* (in the paleogeographic sense) also comprises the ICM to the east. The Sesia-Dent Blanche units lie on top of the Schistes Lustrés ophiolite-bearing units. They derive from an extensional allochthon detached from the Adria margin that was included into the subduction channel during Alpine subduction (Fig. 3C; Manzotti *et al.*, 2014; Giuntoli *et al.*, 2018).

### 2.2 Paleogeography

The European proximal margin is clearly recognized in the External Crystalline Massifs (ECM) with syn-rift fault escarpments draped with Early Jurassic chaotic to graded breccias (Lemoine *et al.*, 1986). Instead, the distal margin of the European continent is preserved in the Briançonnais domain bounded to the SE by the Middle Jurassic-Cretaceous Piemonte-Liguria Ocean (Figs. 3C, 4E). By the end of the Permian, the Briançonnais crust formed the northeastern tip of Iberia (Stampfli *et al.*, 2002; Stampfli and Hochard, 2009) separated from the External zones by the East Variscan dextral Shear Zone (Ballèvre *et al.*, 2018), then it rifted from the Europe proximal margin during the Jurassic, allowing the Valais oceanic branch of Alpine Tethys to moderately spread during the Early Cretaceous (Handy *et al.*, 2010; Loprieno *et al.*, 2011).

Rifting affected the entire Briançonnais domain during the Early Jurassic (Lemoine *et al.*, 1986; Pantet *et al.*, 2020). This

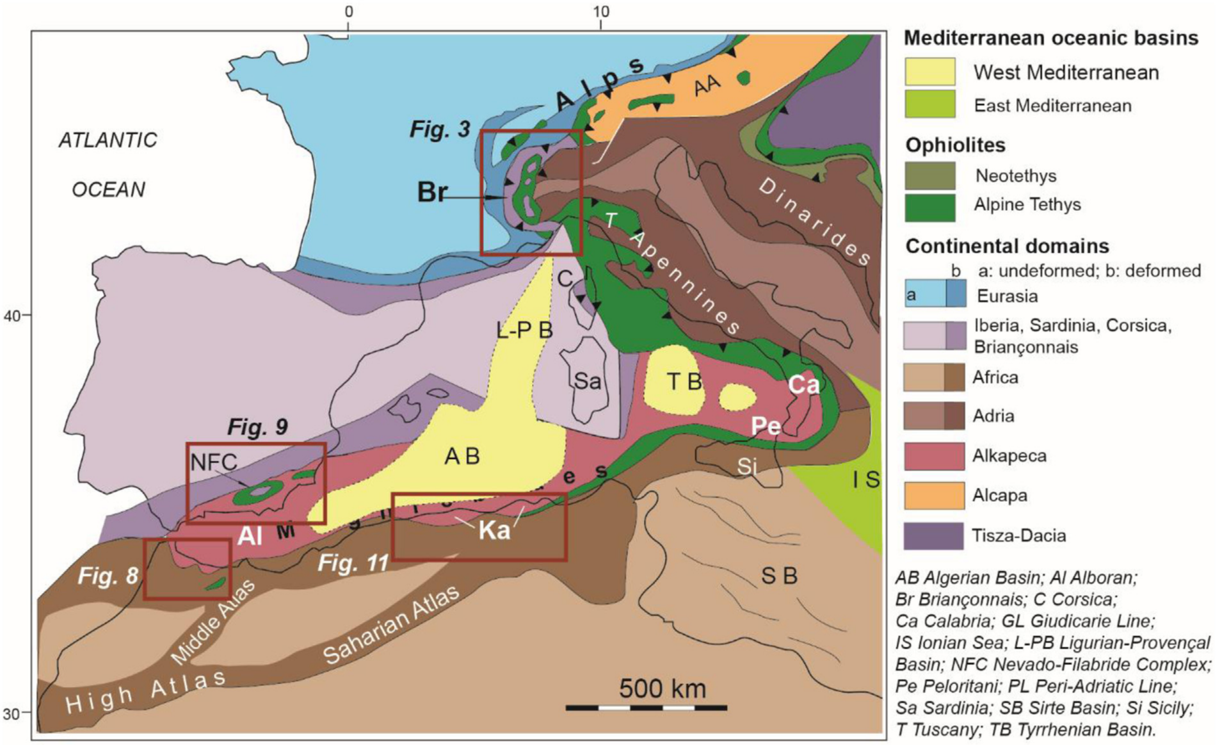


**Fig. 2.** The Alpine belts of Western Europe and North-Africa with location of the Briançonnais and Al-Ka-Pe-Ca terranes and Mediterranean basins, after Handy *et al.*, (2010), modified. AA: Austrian Alps.

is recorded by block tilting and subsequent submarine or subaerial erosion of the uplifted blocks (Fig. 4A, B) that resulted in the shedding of breccias in subsiding half-grabens (Fig. 4D, E). Extension of the Briançonnais went on during the Middle-Late Jurassic resulting in its necking, then breakup, which marked the opening of the Piemonte-Liguria Ocean (Mohn *et al.*, 2010). Slow spreading went on during the late Bathonian to late Kimmeridgian and the Piemonte-Ligurian Ocean reached its greatest width during the Early Cretaceous (Li *et al.*, 2013; Le Breton *et al.*, 2020). At that time, the width of the Briançonnais likely approached ~150 km and the whole domain formed a pelagic continental platform as a result of its thermal subsidence (Fig. 4E).

### 2.3 Late Cretaceous-Paleocene extension of the Briançonnais LEPM

Normal-sense paleo-faults within Late Cretaceous and possibly Paleocene calcschists, associated with coarse breccias were described since decades in the classical Briançonnais nappes (Blanchet, 1935; Tissot, 1955; Debelmas and Lemoine, 1966; Bourbon, 1977; Jaillard, 1988; Kerckhove *et al.*, 2005). In the Cerces massif of the "Zone Houillère", 40 km NNW of Briançon (Fig. 3A), the coarse breccias are accumulated within the *Globotruncana* calcschists along an NNW-trending normal fault steeply dipping to the east (Queyrellin Fault; Tissot, 1955). In the Châtelet nappe exposed in the northern slopes of the Upper Ubaye valley, Claudel *et al.* (1997) described normal faults associated with Upper Jurassic breccias that became reactivated during the Late Cretaceous, which again led to the shedding of coarse breccias within the calcschists of the Jurassic fault hanging-wall. Paleo-fault escarpments cutting across the Upper Jurassic limestones of the same nappe can be also observed along the southern slope of the same valley (Fig. 5A). The calcschists that drape the fault scarp include Jurassic blocks of various size (up to 1 m), and they also fill up neptunian dykes within the limestones (Fig. 5B). Further east in the Ubaye valley, a major, Late Cretaceous extensional or transtensional fault is marked by abundant elements of Triassic dolostones and Permian volcanics reworked in the Upper Cretaceous turbiditic calcschists of the newly defined Maurin unit (Fig. 4B; Dana *et al.*, 2023).

In the Acceglio-type units that crop out at the western border of the classical Briançonnais from the Acceglio-Longet antiform to southern Vanoise (Fig. 3), polygenic, chaotic breccias occur above the thin Jurassic carbonates locally encrusted with Fe-Mn "hard-grounds" of Turonian-Maastrichtian age (Fig. 4C). These chaotic breccias exhibit abundant Triassic quartzite and dolostone blocks of various size (up to 100 m-long olistoliths) and frequent calcschist intercalations. They are ascribed to the Late Cretaceous-Paleocene (Michard *et al.*, 2022, and references therein). According to the latter authors, these breccias formed along sub-marine normal faults cutting through more external Briançonnais blocks that were still rich in Triassic carbonates.

The Marguareis massif of the Ligurian Briançonnais offers several exposures of Late Cretaceous faults cutting tilted blocks of Triassic-Jurassic rocks whereby the calcschists make up the main part of the infilling of the half-grabens (Fig. 6A; Michard and Martinotti, 2002), although extension would have started during the Aptian (Bertok *et al.*, 2012). These extensional structures are unconformably overlain by Eocene

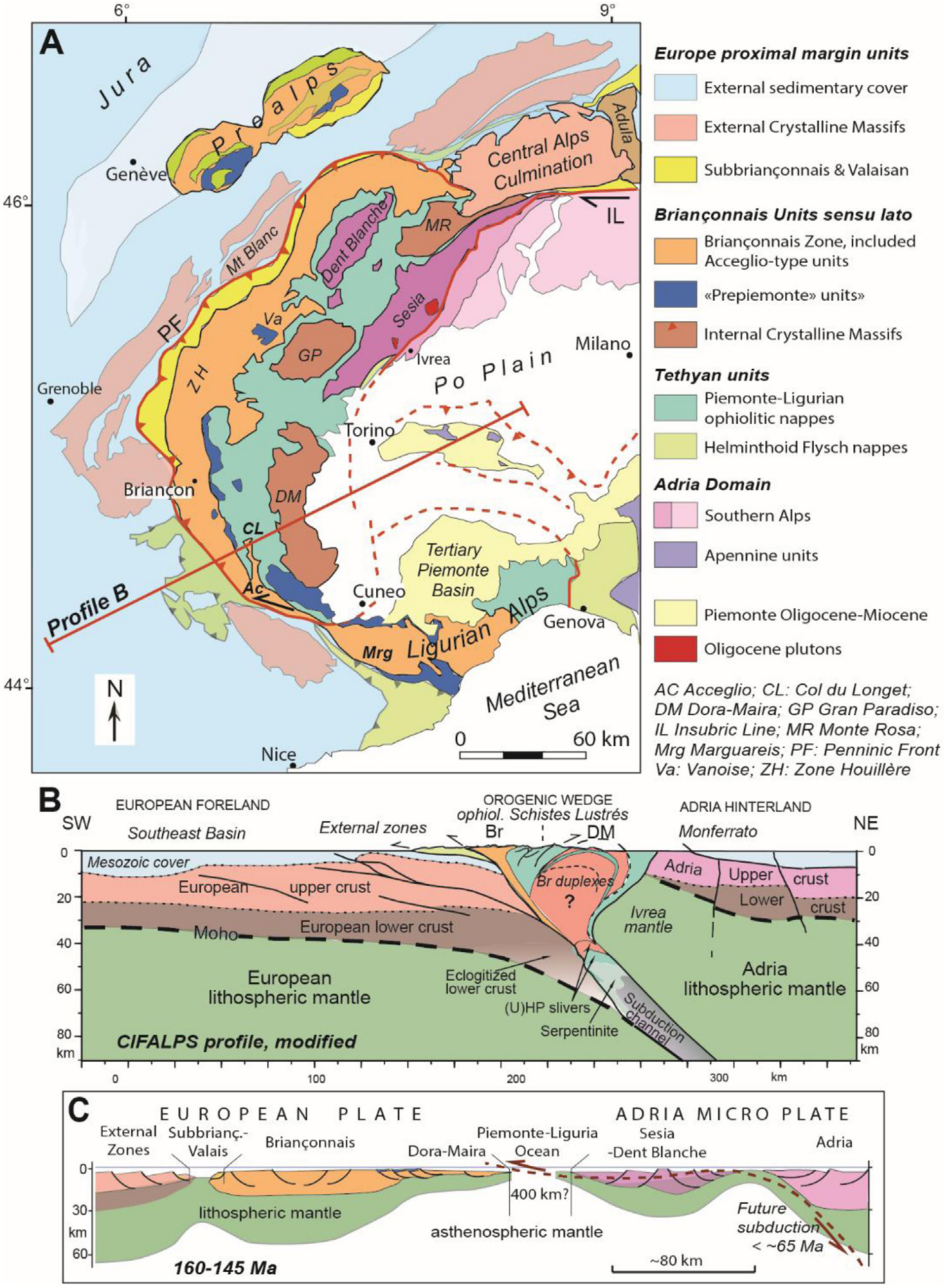


**Fig. 3.** Structural map of the Western Alps (A), crustal-scale cross-section (B) and restored paleogeographic profile (C) after Michard *et al.* (2022a).

deposits (Nummulitic limestones and "Flysch noir") that are only slightly affected by normal faulting above the Cretaceous deposits (Fig. 6B, C).

## 2.4 Relationships with the coeval Alpine subduction

While the Briançonnais passive margin was strongly extending as described above, the lithosphere of the Piemonte-Liguria Ocean was subducting beneath Adria: Alpine subduction occurred from 84 Ma to 35 Ma on the Alpine scale (Handy *et al.*, 2010). Concerning the Western Alps, compression occurred along the western Adria margin between 85-65 Ma in relation with eclogitic metamorphism in the subducting Sesia continental allochthon (Regis *et al.*, 2014; Manzotti *et al.*, 2014; Giuntoli *et al.*, 2018). The uplifted Adria margin is currently regarded as the source of the Upper Cretaceous Helminthoid Flysch that remained in the upper plate of the subduction system and now forms the

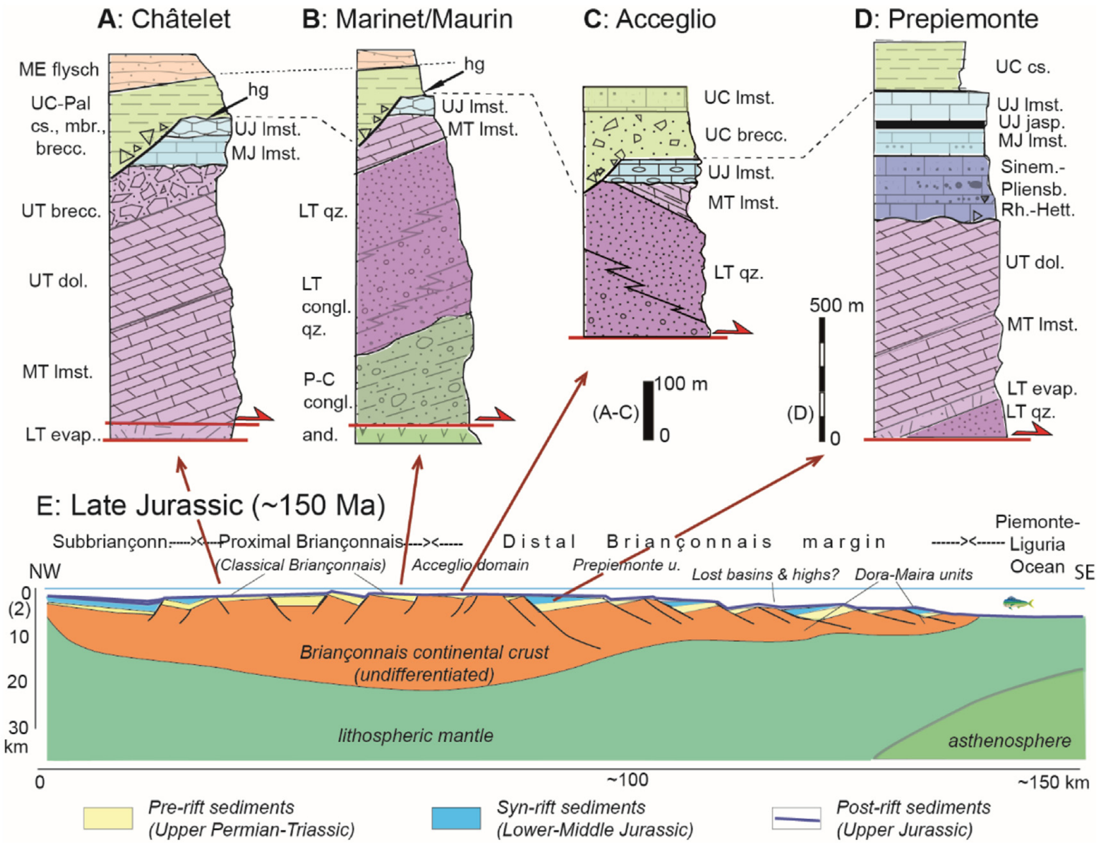


**Fig. 4.** Typical stratigraphic series from the Briançonnais Domain (A-D) located from W to E along the restored paleogeographical profile of the Briançonnais (E), after Michard *et al.* (2022), Dana (2022) and Dana *et al.* (2023), adapted. Vertical scale exaggerated between (E).Stratigraphic abbreviations: L/M/U: Lower, Middle, Upper; P-C: Permian-Carboniferous; T Triassic; J Jurassic, C Cretaceous; Pal Paleocene; E Eocene. Lithologies: and. andesites; brecc. breccias; congl. conglomerates; cs. clastic/pure calcschists; dol. bedded dolostones; evap. evaporites; hg: Fe-Mn hard-ground; jasp. jaspers; lmst. clastic/pure limestones; mbr. microbreccias; qz. quartzites.

uppermost nappes of the external border of the Western Alps (Fig. 3).

The onset of the southeast-ward subduction of the Piemonte-Liguria slab (Alpine subduction) is correlated with the abrupt change in the displacement of Africa *vs.* fixed Eurasia at 84 Ma (Rosenbaum *et al.*, 2002; Schettino and Turco, 2011). The Sesia continental allochthon rifted off Adria entered the subduction zone between 85-72 Ma (Regis *et al.*, 2014; Manzotti *et al.*, 2014; Giuntoli *et al.*, 2018), and subduction of the Piemonte-Liguria Ocean began before ~60 Ma (Agard *et al.*, 2002; Agard, 2021). The Briançonnais was totally subducted between 40-35 Ma (Bonnet *et al.*, 2022). We may approximately assess the distance of the Briançonnais domain from the subduction zone at the time it was affected by extension, *i.e.*, mainly during the Santonian-Ypresian (~85-50 Ma). From 84 Ma to 35 Ma, North-Africa moved toward Eurasia by ~300 km (mean velocity 0.6 cm/y; Rosenbaum *et al.*, 2002). By 45 Ma, the external Briançonnais domain received the Eocene turbiditic sediments ("Flysch noir") that were deposited in the subduction trough along the Adria overriding plate (Fig. 7A). About 10 My later, the Briançonnais was totally subducted (Fig. 7B), the Dora-Maira crust being at 100 km depth at least, which suggests subduction velocity close to 1 cm/y. Assuming an intermediate velocity of 0.7 to 0.8 cm/y, the Briançonnais leading edge would have been at a distance of 175-200 km from the subduction channel by 70 Ma (Fig. 7C). This location corresponds to the width of the bending domain related to the subduction and where stresses reach their maximum (Capitanio *et al.*, 2007; Goes *et al.*, 2008). Lithospheric bending seemingly concentrates most of the resisting forces (Bellahsen *et al.*, 2005), which would account for extensional faulting of the Briançonnais at the extrados of the bending zone. Slab pull exerted by the ~90 Ma-old, cold Tethyan lithosphere, potentially increased by avalanching of the slab into the lower mantle (as suggested for the Sirte basin by Capitanio *et al.*, 2009), and curvature of the subduction zone in map view were considered by Michard *et al.* (2022) as candidates to explain the late extensional phase of the Briançonnais archetypal LEPM.

## 3 The Northern Tethyan margin in the Internal Zones of the Maghrebides

### 3.1 General

As reported in the Introduction section, the Internal Zones of the Maghrebides consist of the Alkapeca terranes (Fig. 2), which initially would have formed a large, single continental block ("Mesomediterranean microplate"; Guerrera and Martín-Martín, 2014), or more likely a ribbon-shaped continental block moderately rifted off Iberia

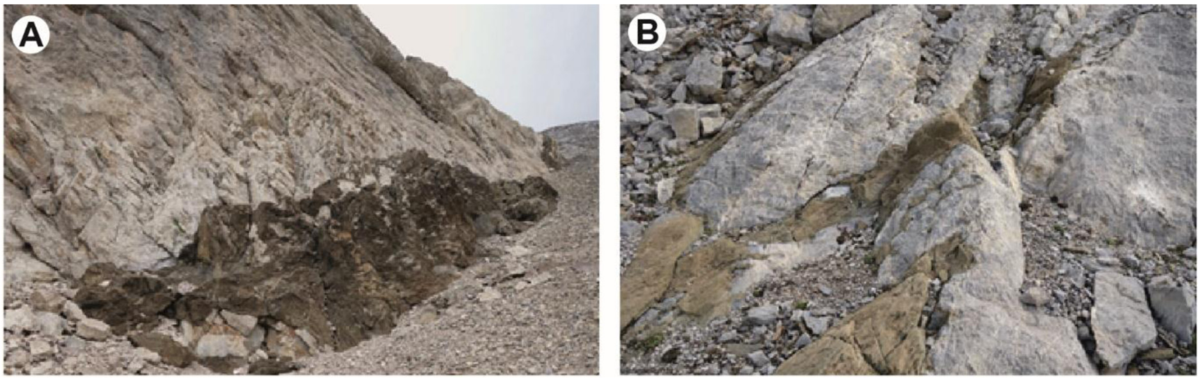
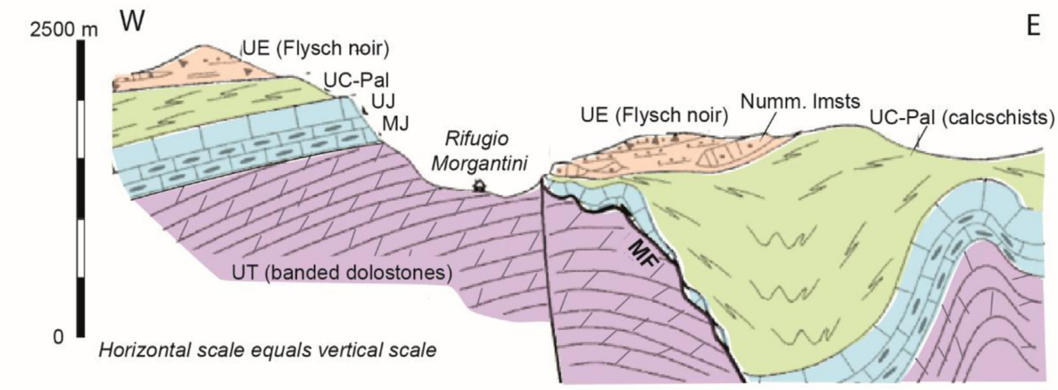
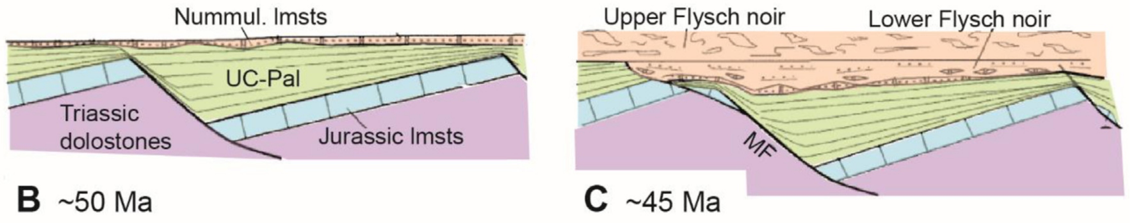


**Fig. 5.** Late Cretaceous fault in the Buc de Nubiera ("Cloudy Peak", 3219 m a.s.l.), Châtelet nappe, Upper Ubaye valley. A: South-facing fault escarpment cutting across the Upper Jurassic limestones; the calcschists (dark) include blocks of limestones. By place, Fe-Mn hardground overlies the fault escarpment. B: Neptunian dykes filled with calcschists in the hanging-wall of the fault about 200 m from (A). Courtesy of J.-P. Bouillin (2022); see also Claudel *et al.* (1997).



**A** Cross-section - MF: Morgantini Fault



**B** ~50 Ma

**C** ~45 Ma

**Fig. 6.** The Morgantini Fault, a case of Late Cretaceous normal faulting reactivated during the Eocene in the Ligurian Briançonnais (Marguareis massif); after Michard and Martinotti (2002), modified. A: Present cross-section. B, C: Interpretation.

during the Mesozoic (Stampfli and Hochard, 2009). Alkapeca fragments were carried onto the African and south-eastern Iberia margins during the Late Eocene-Miocene back-arc opening of the Mediterranean basins (Van et *et al.*, 2014 Van Hinsbergen *et al.*, 2014, Van Hinsbergen *et al.*, 2020). Thus, before this dramatic change, the various Alkapeca terranes were located at the northern margin of the Piemonte-Ligurian-Maghrebian Ocean, like the Briançonnais.

In this section, we will try to assess the markers of Late Cretaceous-Paleocene extensional deformation also present in the Maghrebides terranes. Within these terranes, the potential records of such extension within the Alkapeca paleomargin should be searched for in the so-called "Dorsale calcaire" units. They form elongated crests ("dorsales") of carbonate rocks (dolostones and limestones) that were first defined in the Rif belt (Fallot, 1937). Durand-Delga (1969) defined the Kabylian Dorsale as the eastern continuation of the Rif Dorsale. The continuation of the Rif Dorsale in the Central Betics was described by Durand-Delga and Foucault (1967), and since then a string of Dorsale (or Frontal) units was mapped in the Western Betics reaching from Estepona-Argüelles all the way to the north of Granada (Jabaloy-Sánchez *et al.*, 2019; see below). The homology of the Dorsale units of the Betics, Rif and Kabylias with the those of the Peloritani Mts (Sicily) and Calabria

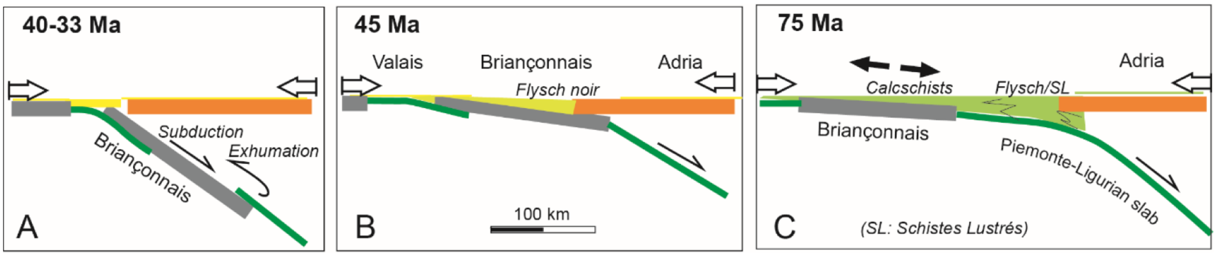


**Fig. 7.** Restoring the location of the Briançonnais with respect to the Alpine subduction zone at three particular times, starting from the youngest stages. A: End of Briançonnais subduction and ongoing exhumation processes. B: Latest, pre-subduction sedimentation over the external Briançonnais (Eocene "Flysch noir"). C: Paleogeography during the Santonian-Maastrichtian, assuming plate convergence velocity equal ~0.8 cm/y. Large empty arrows: plate convergence; large black arrows: crustal extension. Vertical scale equals horizontal scale.

was documented by Bouillin (1986) and Bouillin et al. (1986). These authors identified the former European passive margin, located north of the Maghrebian Flyschs basin (Ligurian-Maghrebian Ocean) in the 2,000 km-long rosary of carbonate Dorsale units. However, it is worth noting some differences between the eastern and western transects: in the Rif and Betics, the Dorsale only occurs at the front of the Alboran basement units and includes thick Triassic dolomitic formations, whereas the Dorsale units from the Kabylias to Calabria stratigraphically overlie in many cases the basement units and only consist of Hettangian-Sinemurian limestones.

Focusing to the outcrops between Alboran and Sicily, the Dorsale is everywhere made up of several, virtually non-metamorphic units (with the noteworthy exception of the Nieves; Mazzoli and Martín-Algarra, 2011; Bessière, 2019) stacked at the front of the metamorphic units. For that reason they were re-named "Frontal Units" in the Betics (Jabaloy-Sánchez *et al.*, 2019). In most transects, the stacked units can be classified as "internal", "median" and "external" according to their stratigraphical series that become more and more complete going toward the Maghrebian Flyschs units, respectively. The northernmost Flysch units, labeled Mauretanian Flysch, locally preserved basal units whose stratigraphic sequence is transitional to the most external Dorsale sequences (*e.g.*, Ouareg sequence, Olivier *et al.*, 1996; Contrada Lanzeri Formation, Bouillin *et al.*, 1995). The incomplete successions of the Internal Dorsale are transitional toward the still more reduced successions that are occasionally preserved onto the basement units (*e.g.*, Malaguides-Ghomarides in the Betic-Rif orogen; El Kadiri *et al.*, 1989).

In the Alboran Domain, the Dorsale units are detached from their former continental basement on the evaporitic Late Permian-Middle Triassic redbeds. Many authors assumed with Didon *et al.* (1973) that the Dorsale units were initially located above the Malaguide-Ghomaride Paleozoic basement (*e.g.*, Michard *et al.*, 2002, 2006). Conversely, and in line with Chalouan *et al.* (2008), we adopt here the "Swiss hypothesis" (Trümpy, 1973; Wildi *et al.*, 1977; Nold *et al.*, 1981) that considers the Dorsale as detached from the Alpujarrides-Sebtides on the Middle Triassic pelitic beds. This is consistent with the thinning of the Alpujarride-Sebtide crust and early exhumation of the Ronda-Beni Bousera peridotites underneath (Farah *et al.*, 2021). The pre-orogenic structure of the Alboran Domain passive margin is discussed in Michard *et al.* (2023) and shown consistently hereafter.

In Algeria, some Dorsale series where Triassic evaporitic beds are lacking preserve stratigraphic relationships with their Devonian-Carboniferous basement (*e.g.*, Chellata internal Dorsale, Gélard, 1979; Lesser Kabylia, Raoult, 1975). The Hettangian-Sinemurian carbonates (mostly limestones, with some basal dolostones) may exceed 600 m thickness and make up the major part of the Dorsale stratigraphic successions. They record the rifting events with Sinemurian-Pliensbachian breccias and cherty limestones formations whereas the Middle-Upper Jurassic are pelagic and condensed (*e.g.*, Wildi, 1979; Cattaneo *et al.*, 1999; Raoult, 1975).

## 3.2 Cretaceous-Paleocene successions

### 3.2.1 Alboran Domain

The northern Rif exhibits several exposures of Cretaceous-Paleocene deposits preserved beneath the unconformable, Eocene shallow water limestones or Eocene-Oligocene sandstones and marls. In the Hafat Ferkenich unit (Internal Dorsale; Fig. 8B), besides the Liassic deep unconformity, two unconformities associated with chaotic breccias or olistostromes are observed, i) an older one below the Berriasian-Valanginian pelagic limestones, and ii) a second one below the Campanian-Maastrichtian purple-greenish marls, both of them ascribed to extensional faulting (Fig. 8C; El Kadiri *et al.*, 1989). Conspicuous chaotic breccias of Tithonian-Berriasian age, involving radiolarites and Aptychus micrites, crop out near Cherafat at the southern boundary of the External Dorsale unit (Chalouan *et al.*, 2011; Michard *et al.*, 2023, their Fig. 2.13). Late Jurassic extension is similarly recorded by breccias and radiolarites in the Ouareg sequence at the very base of the Mauretanian Flysch (Olivier *et al.*, 1996).

In the Bokoya massif further to the east (Fig. 8A), Mégard (1969) described conglomerates and micro-conglomerates in the Upper Cretaceous calcareous marls. The age of the reworked elements spans from Paleozoic to Late Cretaceous. However, the poor quality of the outcrops hampers observations of potential paleofaults of Cretaceous age.

Going west to the Strait of Gibraltar, the Jebel Musa Group (southern Hercules Column of the Strait of Gibraltar), which is transitional between the Internal and External Dorsales, offers clear records of Lower Cretaceous syn-sedimentary normal faults and tilted blocks (Fig. 9A; El Hatimi and Duée, 1989). The "Predorsalian" units (Olivier, 1990) are transitional between the External Dorsale and the uppermost Maghrebian

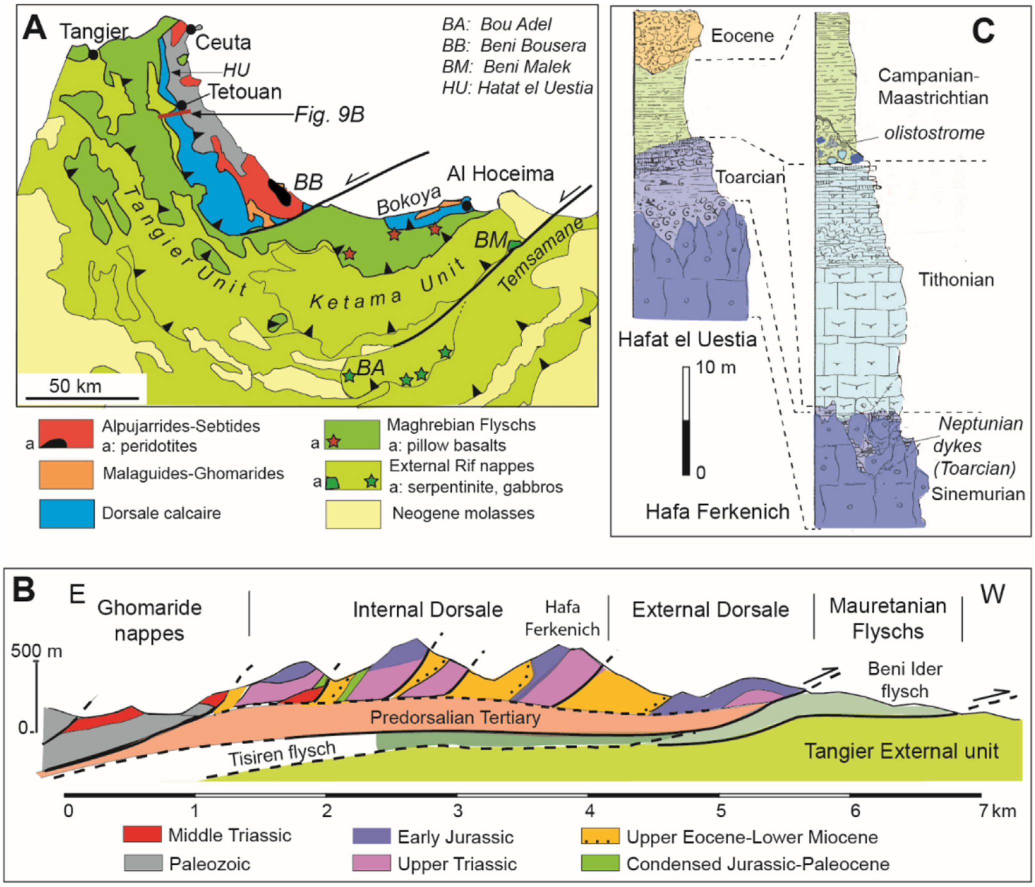


**Fig. 8.** The Rifian part of the Alboran Domain (Fig. 2 for location). A: Sketch map of the northern Rif, after Michard *et al.* (2018), modified. B: Cross-section of the Dorsale Calcaire along the Tetouan transect, after Chalouan *et al.* (2011). C: Stratigraphic columns of the Internal Dorsale, after El Kadiri *et al.* (1989), modified. See (A) for location of Hafa el Uestia, and (B) for Hafa Ferkenich. Three extensional events are highlighted: end of Early Jurassic, Tithonian and Late Cretaceous. The Campanian olistostrome contains elements of the various Jurassic facies.

Flyschs units (Fig. 8B), *i.e.*, the Mauretanian Flyschs (Tisiren and Beni Ider nappes in the Rif nomenclature). These distal units contain breccias with radiolaritic matrix and fragments in their Upper Jurassic and Lower Cretaceous beds, followed upward by bituminous calciturbidites in the Cenomanian-Turonian and sandy calciturbidites and breccias in the Campanian beds (Fig. 9B). The Upper Cretaceous sedimentary facies favorably compares with that of the coeval beds of the Mauretanian Flyschs. Thus, Olivier (1990) concluded that extensional faults were permanently active between the External Dorsale and the Flysch basin.

The Dorsale Calcaire or Frontal units of the Betic Cordilleras are exposed all around the western Internal zones of the belt (Fig. 10A-C). They are similar to those of the Rif belt (Jabaloy-Sánchez *et al.*, 2019), except the high-temperature metamorphism (up to 600 °C; Bessière, 2019) of the Nieves unit, linked to its particular tectonic position (Mazzoli and Martín-Algarra, 2011; Bessière, 2019). In particular, the Pereila Units (Fig. 10D) are equivalent to the disrupted Predorsalian units of the Rif in contact with the Flysch units. Among the Pereila units, the Argüelles-type units (Fig. 10E) contain Valanginian breccias and carbonate turbidites bearing *Microcodium* indicating a Paleocene age.

### 3.2.2 Kabylias

In Greater Kabylia (Fig. 11A), the Merkalla unit of the External Dorsale (Fig. 11B) exhibits conglomerates interbedded in the Upper Jurassic carbonates-radiolarites formations, in the Lower Cretaceous marls and again in the Aptian-Albian marls (Naak *et al.*, 1989). Nearby, Upper Cretaceous pelagic foliated marls (calcschists sensu lato) conformably overlie Liassic limestones affected by small normal faults; beneath the pelagic Cretaceous beds, the surface of the Liassic limestones are perforated by lithophagous animals; this setting suggests an extensional tectonic regime under submarine conditions during Late Cretaceous times (Fig. 11C, D). In the Median Dorsale of the Chellata Massif, Gélard (1979) described Upper Cretaceous formations rich in syn- sedimentary conglomerates and directly transgressive, although without unconformity, onto the Upper Jurassic limestones (Fig. 11E). Likewise, in another unit (Amkrouz Unit) of the same area, Gélard (1979) described Thanetian beds conformably overlying Permian-Triassic formations. Further to the east, in an External Dorsale unit (Tagragra Unit) and a Pre-Dorsale type unit (Sammer Unit), Coutelle (1979) described Turonian-Paleocene formations rich in microbreccias and conglomerates, either

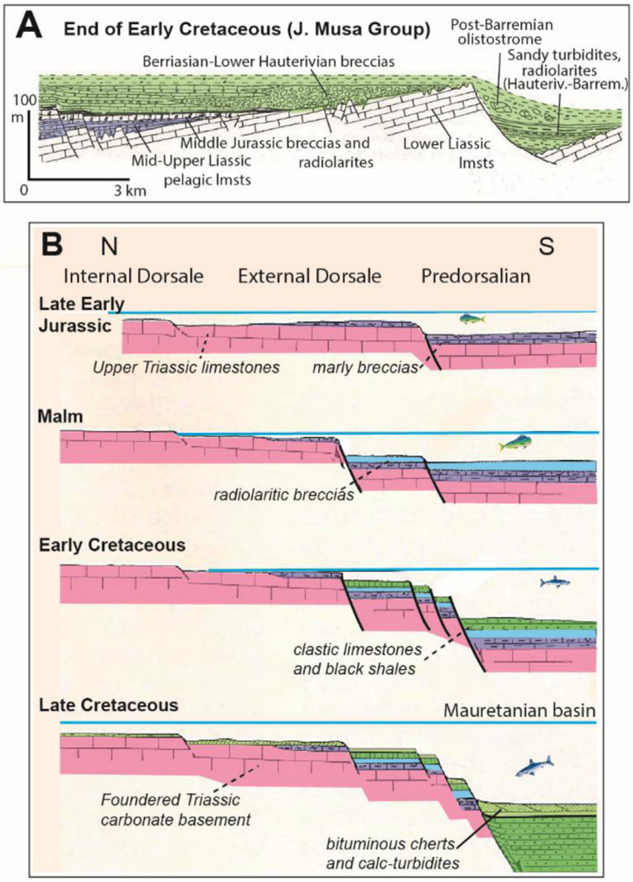


**Fig. 9.** Jurassic-Cretaceous extension of the Internal Rif paleomargin. A: after El Hatimi and Duée (1989); J.: Jebel. B: after Olivier (1990), modified.

bedded or massive, some of them including large boulders of Jurassic-Early Cretaceous clypeine limestones (Fig. 11F).

In Lesser Kabylia, the External Dorsale remained partly attached onto its Paleozoic basement (Fig. 11G). The western and eastern part of the area were studied many years ago by Durand-Delga (1955) and Raoult (1974), respectively. Invaluable stratigraphical data were made available by these works (Fig. 12), but some structural descriptions deserve tentative re-interpretations. Two distinct events leading to the shedding of breccias or coarse conglomerates can be distinguished. The Sinemurian breccias of the Rhedir unit (Fig. 12B) records the rifting event responsible for the opening of the Central Atlantic and Alpine Tethys. Conversely, the micro-breccias, calc-turbidites and coarse conglomerates of the Upper Cretaceous-Paleocene formations beds of the Rhedir and Tengout units (Fig. 12B, C) most likely formed due to extensional faulting since no previous folding event is described. The "unconformity" described by Raoult (1974) at the very base of the Tengout unit is no longer invoked by Raoult (1975) and likely corresponds to a less than 50 m-thick shear zone. Likewise, a meter-size body of *Globotruncana* limestones inserted in faulted Liassic limestones that was interpreted (Raoult, 1974) as a pinched syncline (Fig. 13A) could rather represent infilling of a cavity developed in a submarine fault scarp, since the Liassic limestones cannot deform ductilely, being non-metamorphic. At a larger, hundred meters-scale, the interpretation proposed by Durand-Delga (1959) for the Campanian-Maastrichtian unconformity over the Liassic limestones at Kef Sema in western Lesser Kabylia (Fig. 13B) is dubious as it implies isoclinal folding of the massive, non-metamorphic Liassic limestones. Instead, the Kef Sema structure could result from a twofold evolution involving, i) the onlap of the Upper Cretaceous deposits over extensional tilted blocks of the Triassic-Liassic Dorsalian series, and ii) stacking of thrust slivers during the Late Eocene compressional phase (personal comm. JP. Bouillin, October 9, 2022).

Bouillin (1986, his Fig. 3B) already interpreted the relationships of the Internal Dorsale, External Dorsale and Mauretanian Flysch basin in the frame of extensional faulting active from the Early Jurassic all the way to at least the end of Early Cretaceous. The Mauretanian Flysch accumulated in the Maghrebian oceanic basin next to the Kabylian margin, and its stratigraphic succession (Fig. 12, right) actually records shedding of coarse breccias sourced in the Dorsale domain during the Late Cretaceous-Paleocene span of time.

### 3.2.3 Peloritan Dorsale

In the Sicilian segment of the Maghrebides, the Peloritan Dorsale was first compared to the Kabylian by Bouillin (1986). This narrow strip of calcareous sediments is thrusted by the basement of the Peloritan massif and in turn thrusts the underlying Sicilides, the equivalent of the Maghrebian Flysch, towards the southwest. Subsequently, Bouillin *et al.* (1992) interpreted the Mesozoic units of the various units referred to the Peloritan Dorsale as the record of a narrow Jurassic passive margin, about 25 km-wide only, formed by extensional or rather transtensional faulting from the Pliensbachian to the Late Jurassic. However, Bouillin *et al.* (1999) improved the description of the neptunian dykes that crosscut fault scarps within the Paleozoic schists at the base of the Capo di San Andrea unit near Taormina showing they not only contain Jurassic infilling (Truillet, 1969-1970), but also Lower and Upper Cretaceous subsequent infilling (Fig. 14). The submarine scarps of this distal margin are incrusted by Fe-Mn hardgrounds and remained exposed on sea bottom for about 140 Ma, being sealed by Eocene marls that also unconformably overlie the Jurassic condensed layers. Late Jurassic extension is also recorded in the Contrada Lanzeri Formation at the very base of the Mauretanian flysch of Monte Soro (Bouillin *et al.*, 1995).

# 4 Discussion

## 4.1 Alpine subduction of the Ligurian-Maghrebian oceanic lithosphere

As reported above, subduction of the Piemonte-Liguria slab beneath Adria is well-documented in the Western Alps transect between 85-35 Ma (Fig. 8; Handy *et al.*, 2010; Manzotti *et al.*, 2014), consistent with the onset of Africa-Eurasia convergence at 87-84 Ma (Rosenbaum *et al.*, 2002; Handy *et al.*, 2010; Schettino and Turco, 2011). However, such a Late Cretaceous-Early Eocene SE-dipping subduction was not recognized so far in the Maghrebian transect. Jolivet and

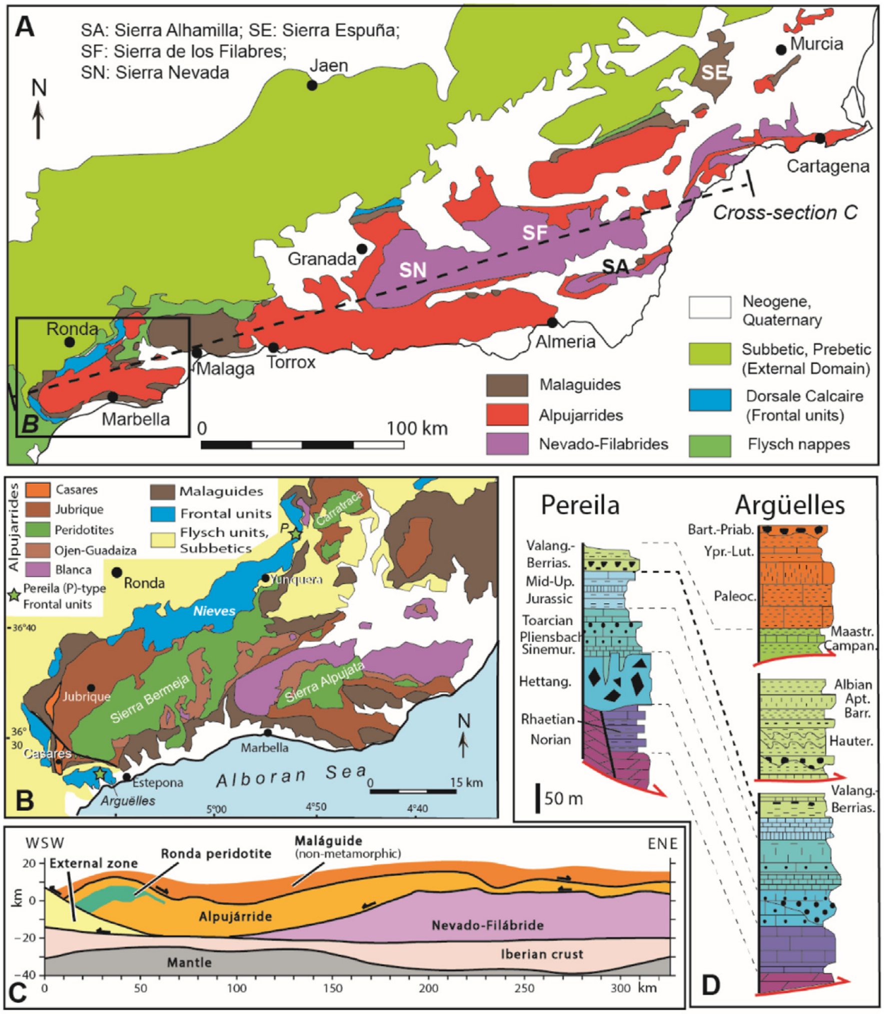


**Fig. 10.** Betic part of the Alboran Domain (Fig. 2 for location). A: Overall map of the Betic Internal Zones, basically made up of the nappe stack formed at the expense of the Alboran Domain basement, strongly thinned during its Miocene eastward extension (after Martín-Algarra *et al.*, 2019). B: Enlarged map of the western Betics showing the Frontal units (Dorsale Calcaire) and peridotites massifs (after Balanyá *et al.*, 1997). C: Longitudinal cross-section (after Platt *et al.*, 2013) emphasizing the westward thrusting and thinning of the nappe stack, which is separated from the External Zones by a major, dextral compressional strike-slip (Iberian-Betic Shear Zone). D: Two stratigraphic columns from the Frontal Units (after Jabaloy Sánchez *et al.*, 2019). See (B) for location. *Lithologies*: Norian: red pelites, gypsum, dolostones; Rhaetian: alternating dolostones/limestones; Hettangian: dolomitic coarse breccia; Sinemurian-Toarcian: cherty/marly limestones; Middle-Upper Jurassic: cherty/marly limestones, radiolarites; Berriasian to Barremian: varicolored claystones and marls, carbonate breccias, neptunian dykes; Aptian-Albian: sandstones, shales; Campanian-Maastrichtian: varicolored claystones and marls, carbonate microbreccias, fine-grained sandstones.

Facenna (2000) and Frizon de Lamotte *et al.* (2011) featured for the Paleocene and the Santonian-Campanian, respectively, a NW-dipping subduction along the Alkapeca blocks, similar to the future Late Eocene-Miocene subduction. In contrast, Leprêtre *et al.* (2018) featured a passive margin along the southeastern border of Alkapeca for the Paleogene. These Authors suggest that Africa-Eurasia convergence was accommodated by subduction of the “West-Ligurian Tethys” (the “Betic Ocean” of Puga *et al.*, 2011) slab beneath Alkapeca, and by a minor continental subduction of the African margin itself. However, on the one hand the nature of the “Betic Ocean” is controversial: according to Gomez-Pugnaire and Munoz (1991), Jabaloy Sánchez *et al.* (2019) and Porkoláb *et al.* (2022), it was rather an extended OCT domain off southwestern Iberia and its width was restricted. On the other hand, HP-LT metamorphism of the Nevado-Filabride ophiolitic rocks is now dated at 38-27 Ma ($^{40}$Ar/ $^{39}$Ar dating; Porkoláb *et al.*, 2022), which points to a late Paleogene subduction beneath the Alpujarrides-Malaguides continental units. Consistent Sm-Nd bulk-garnet ages were obtained by Aerden *et al.* (2022) from the Alpujarride-Sebtide complex (35–22 Ma) and from the Nevado-Filabride complex (35–13 Ma). Finally, the medium pressure-low temperature metamorphism of various Rif-Tell coastal massifs is now better dated from the

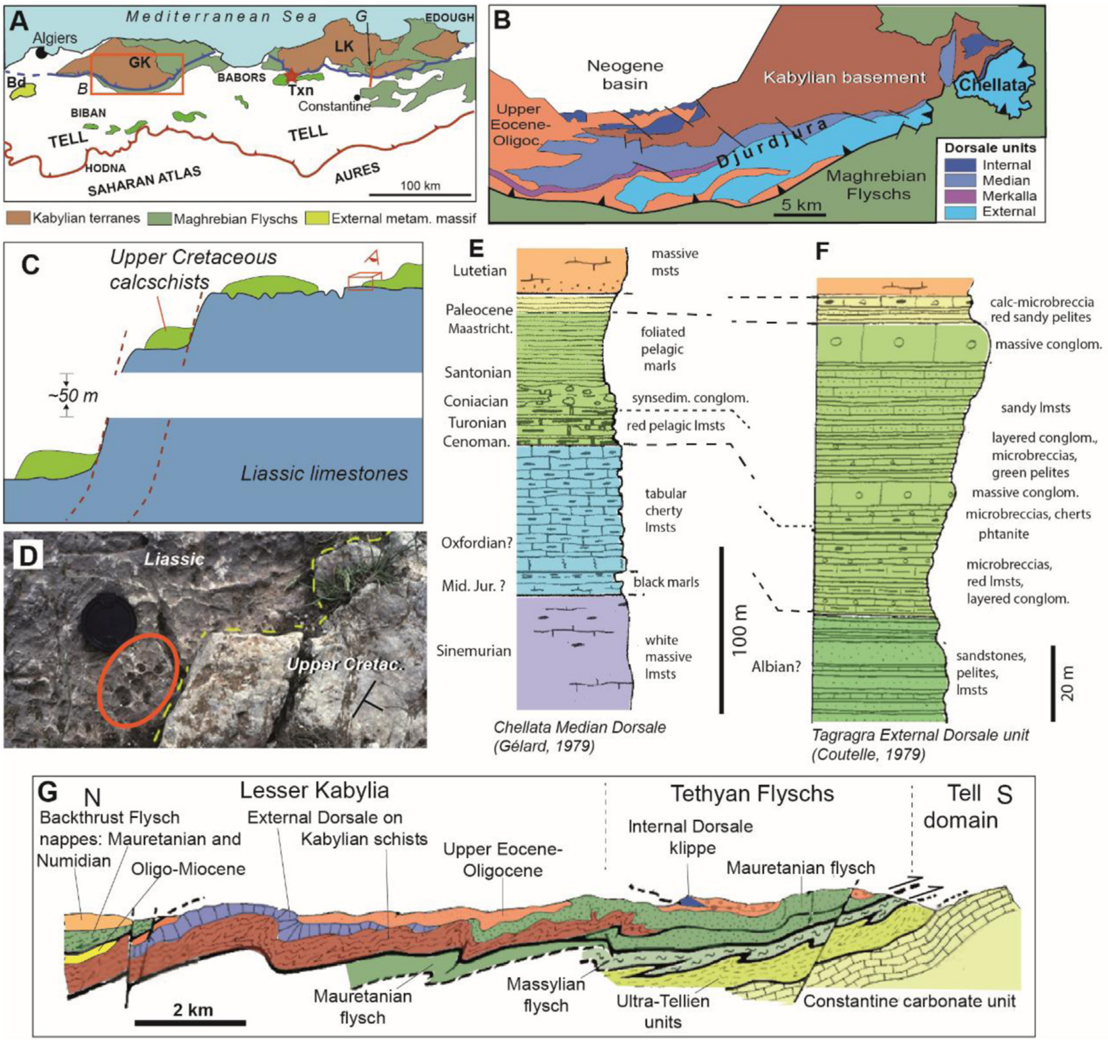


**Fig. 11.** A: Structural map of the Kabylias and adjacent units, redrawn after Leprêtre *et al.* (2018), modified. Bd: Blida; GK/LK: Greater/Lesser Kabylia; Txn: Texenna. Blue heavy line: Kabylian thrust contact over Flyschs and Tell units. Red heavy line: thrust contact of the Tell units over Atlas foreland. – B: Map of the Dorsale units in Greater Kabylia (framed in A) after Cattaneo *et al.* (1999), modified. C, D: Upper Cretaceous onlap on faulted Liassic limestones in the External Dorsale, close to the Merkalla Lower Cretaceous basin. Perforations by benthic animals are shown on the onlap of the *Globotruncana* calcschists (courtesy J-P Bouillin, July 2022). E: Upper part of the stratigraphic series of the Median Dorsale in the Chellata massif, after Gélard (1979). F: Tagragra External Dorsale sliver (Pre-Dorsale type unit), after Coutelle (1979). G : Profile across Lesser Kabylia, after Raoult (1974), modified (see A for location).

Oligocene-Miocene than from the Cretaceous (Negro *et al.*, 2008; Jabaloy-Sánchez *et al.*, 2015; section 4.2).

We reported above on the post-rifting, extensional regime documented in the Briançonnais LEPM from the Late Jurassic to Early Eocene, with its climax during the Late Cretaceous-Paleocene, which represents an ultimate phase of extension coeval with the Alpine subduction (Fig. 7C). Admittedly, part of the throw of the Late Cretaceous-Paleocene faults of the Briançonnais may have been left-lateral as the overall displacement of Africa with respect to Europe was also oblique and left-lateral (Van Hinsbergen *et al.*, 2020). Our examination of the Maghrebide made undebatable that extension or transtension also characterized the Alkapeca paleomargin from the Alboran Domain of the Rif and Betics to the Peloritani units of Sicily during Late Jurassic-Paleocene times. This paleomargin was not an active margin, but a typical LEPM. Based on the occurrence of coarse breccias in the External Dorsale units of Kabylia and in the formerly adjacent Mauretanian Flysch, it appears that extensional faulting was particularly active there during the Late Cretaceous-Paleocene (Figs.11 and 12). This lead us to hypothesize that the Alpine SE-dipping subduction operated along the southeastern margin of the Ligurian-Maghrebian Ocean at least up to the present-day Kabylian transect (Fig. 15). Thus, the restored crustal scale profile between the former Alkapeca and the North-African paleomargin would be as shown in Fig. 16A. Extension of the Alkapeca margin would have occurred coevally with subduction along the African margin of the Ligurian-Maghrebian Ocean for the same reasons as proposed above for the Briançonnais, *i.e.*, mainly bending of the subducting

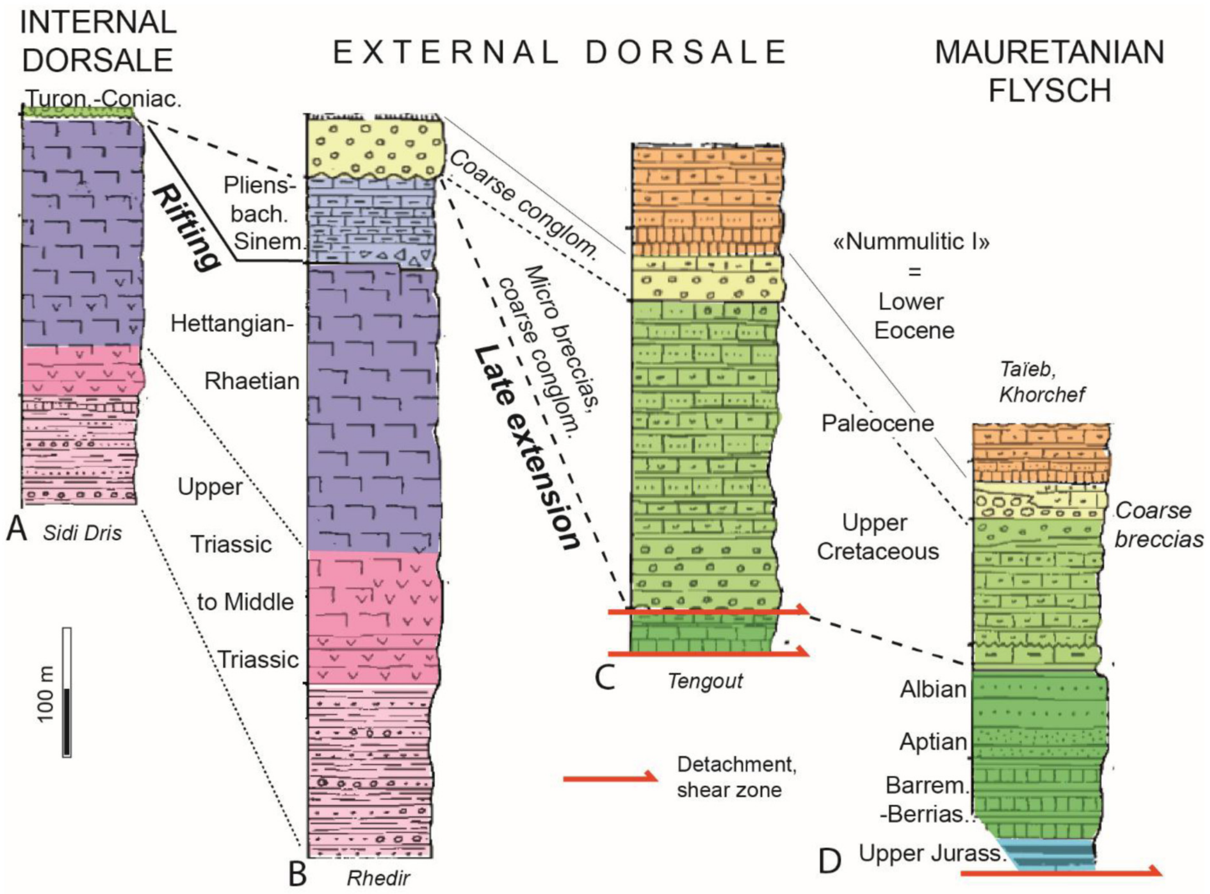


**Fig. 12.** Stratigraphic columns of the Lesser Kabylia Dorsale and adjoining Mauretanian Flysch after Raoult (1974, 1975), modified. The age proposed here for the lowermost formations of the Sidi Dris and Rhedir successions is inspired from the Internal Rif successions (Baudelot *et al.*, 1984).

lithosphere and slab pull. In other words, the Alkapeca terranes would derive from a Late Cretaceous-Paleocene LEPM.

However, the stratigraphic columns of the Betic and Rifian Dorsale Calcaire units (Figs. 9 and 10) suggest that, in the transect of the Alboran Domain, shedding of breccias peaked during the Late Jurassic-Early Cretaceous. This period corresponds to the east-ward displacement of Africa respective to Iberia, and to the spreading of the Alpine Tethys, which then connects with the Central Atlantic (Handy *et al.*, 2010). Therefore, we hypothesize that the coarse, pelagic breccias here considered result from the activity of transtensional faults associated with the major translation of the African plate to the east-southeast (Fig. 15). Further east, the structure of the Kabylian Dorsale Units was interpreted by Bouillin (1992) as the possible result of Jurassic-Cretaceous faulting in the major E-W left-lateral transform zone extending along the outboard of North Africa.

## 4.2 Late Cretaceous deformation of the upper plate

In the Lombardian Alps transect, the Late Cretaceous subduction triggered moderated folding within the Southern Alps that are part of the Adria upper plate. This folding event is exemplified by the “pre-Adamello” NE-trending folds south of the Insubric (Peri-Adriatic) Line and west of the Giudicarie Line (Fig. 2), dated at about 70-60 Ma (Meier, 2003). North of the Insubric Line, the northwest-ward thrusting of the Austroalpine Nappes occurred earlier, between 100-80 Ma (Froitzheim *et al.*, 1997). Half-way to the North-Africa transects, the Tuscany transect offers another indication of the loose coupling between the subducting oceanic lithosphere and the overriding Adria plate. In the typical Tuscany Nappe sequence, the Middle Jurassic Diaspri (jaspers) and Lower Cretaceous Maiolica calci-turbidites are conformably followed upward by the Late Cretaceous lower Scaglia deposits that consist of varicolored shales alternating with subordinate calcilutites and calci-turbidites (Conti *et al.*, 2020; Fazzuoli *et al.*, 1994). The Middle Jurassic to Cretaceous sedimentation over the Tuscany margin are transitional to the coeval sediments of the adjacent Ligurian oceanic domain, and was not deformed prior to the Apennine orogeny.

In the Tellian External Zones of the Maghrebide orogen, several authors claimed that Late Cretaceous compressive or transpressive events (“Albian” and “Campanian” phases) preceded the major folding and thrusting phases of Eocene age (Obert, 1974, 1984; Lepvrier, 1978; Maluski *et al.*, 1979; Vila, 1980). This concept of Late Cretaceous, partly syn-metamorphic folding of the northern Tell (*e.g.*, Babor massif, Fig. 11A) was repeatedly cited afterward (Wildi, 1983; Ricou *et al.*, 1986; Kuhnt and Obert, 1991; Naak, 1996). However, the

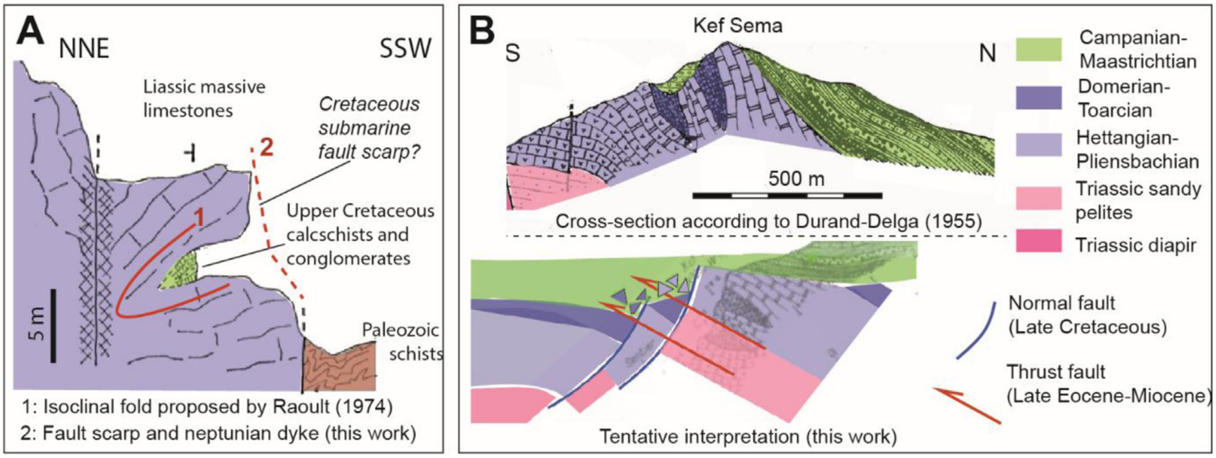


**Fig. 13.** Tentative re-interpretation of particular outcrops from the Dorsale calcaire of Lesser Kabylia. A: The pelagic Upper Cretaceous limestones could represent infilling of a cavity in a submarine fault scarp rather than a meter-size pinched syncline. B: The alleged, hundred meters-size "pinched synclines" of Upper Cretaceous coarse conglomerates of Jebel Sema could be explained by onlap of Cretaceous deposits on extensional tilted blocks subsequently crosscut by Late Eocene thrusts.

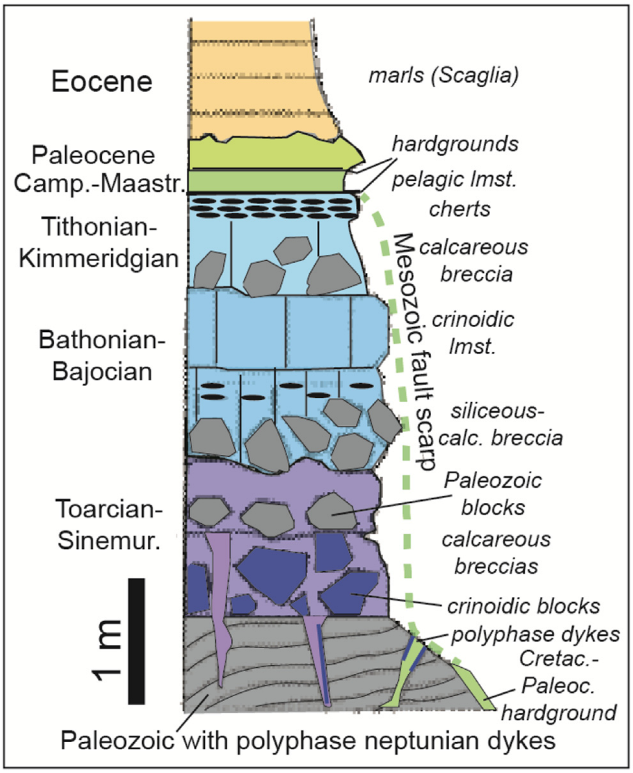


**Fig. 14.** The permanent pelagic fault scarp and associated polyphase breccias and neptunian dykes of the Capo San Andrea unit (Peloritan Dorsale near Taormina), after Bouillin *et al.* (1999), modified.

K-Ar dates supporting this concept have proved to be obsolete and the metamorphism of the "External Metamorphic Massifs" (Leprêtre *et al.*, 2018) is currently referred to the Late Oligocene-Miocene by reference to the Temsamane massif of the Eastern Rif (Negro *et al.*, 2008; Jabaloy-Sánchez *et al.*, 2015). Likewise, the apparently strong structural argument proposed by Obert (1974, his Fig. 4) in support of polyphase Cretaceous folding may be deciphered in terms of progressive ascent of a Triassic diapir (Fig. 17). As a matter of fact, salt diapirs are widespread in the Algerian-Tunisian Tell (Obert, 1986; Jaillard *et al.*, 2017) and in the Rif External Zones (Chalouan *et al.*, 2008; Gimeno-Vives *et al.*, 2020), as well as in the Central High Atlas, Saharan Atlas and Atlantic passive margin, being generally active from Early Jurassic to Late Cretaceous times (Vergès *et al.*, 2017). However, inversion of normal faults occurred as early as the Campanian in the western High Atlas, with syn-sedimentary breccias along the fault and unconformity of the overlying Eocene beds (Froitzheim, 1984; Fekkak *et al.*, 2018). Likewise in the Middle Atlas, the Foum Kheneg natural cross-section shows Maastrichtian-Lower Eocene beds resting unconformably on Liassic limestones; this would be controlled by permanent strike-slip faulting (Herbig, 1988). According to Frizon de Lamotte *et al.* (2009, 2011), lithospheric buckling ("plis de fond") developed in the Atlas system and Sahara platform in relation to the Late Cretaceous Africa-Eurasia convergence. We conclude that the compressional structures coeval with the Alpine subduction in the North-African upper plate are moderate, which compare favorably with what can be observed in the Southern Alps continental margin. This suggests that the subduction zone retreated northwest-ward, in relation with the old age of the oceanic lithosphere (~80 My) and the low-velocity convergence of Africa respective to Eurasia (~0.6 cm/y; Rosenbaum *et al.*, 2002; Handy *et al.*, 2010).

### 4.3 From the Late Cretaceous-Paleocene to the Late Eocene-Oligocene subduction settings

The above discussion led us to propose that a SE-dipping Alpine subduction was also active along the North-African margin during the Late Cretaceous-Paleocene times (Figs. 15 and 16A). On the other hand, the role of a NW-dipping Apennine subduction in the opening of the western Mediterranean basins from ~35 Ma onward was recognized since decades (Royden, 1993; Elter, 1997; Michard *et al.*, 2002, 2006; Jolivet *et al.*, 2008; Molli, 2008; Van Hinsbergen *et al.*, 2014). This implies that a subduction polarity reversal

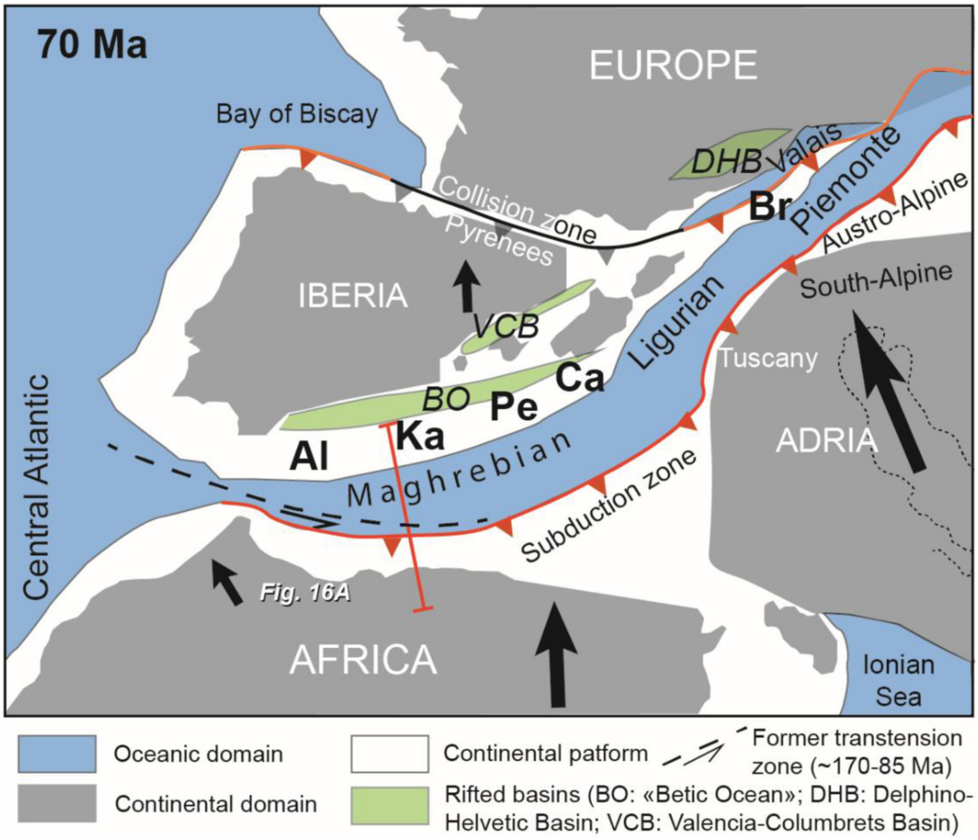


**Fig. 15.** Proposed schematic restoration of the Late Cretaceous paleogeography and geodynamics of the westernmost Alpine area. Middle Jurassic-Early Cretaceous transtensional movement between Africa and Iberia is also shown after Handy *et al.* (2010). Background map after Stampfli and Hochard (2009), simplified. Black arrows: direction and amount of movement from 67 Ma to 35 Ma of underlying plates relative to fixed Europe, after Handy *et al.* (2010).

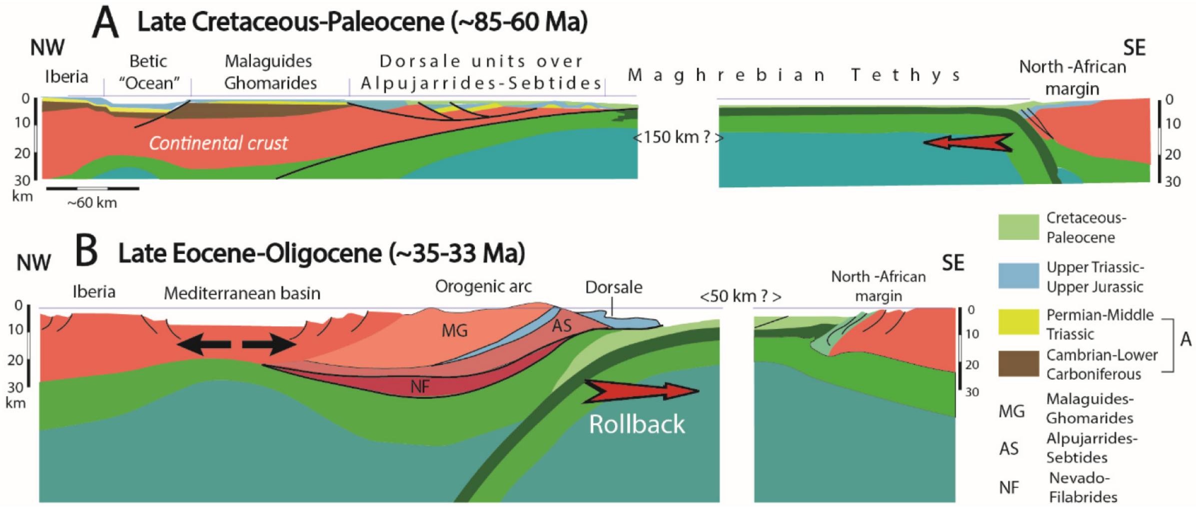
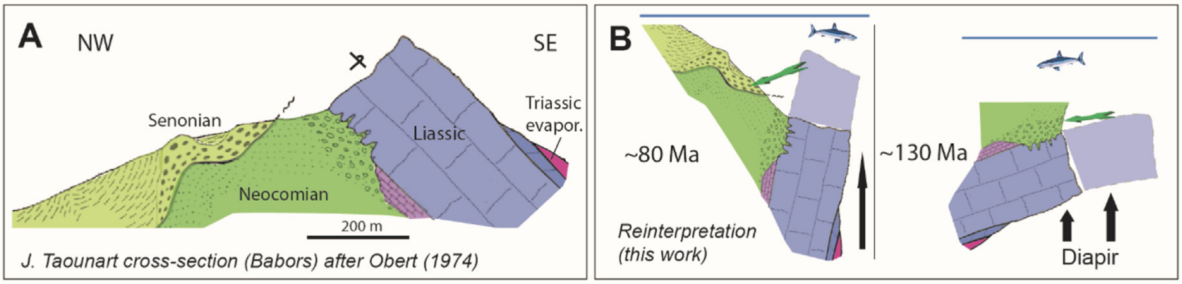


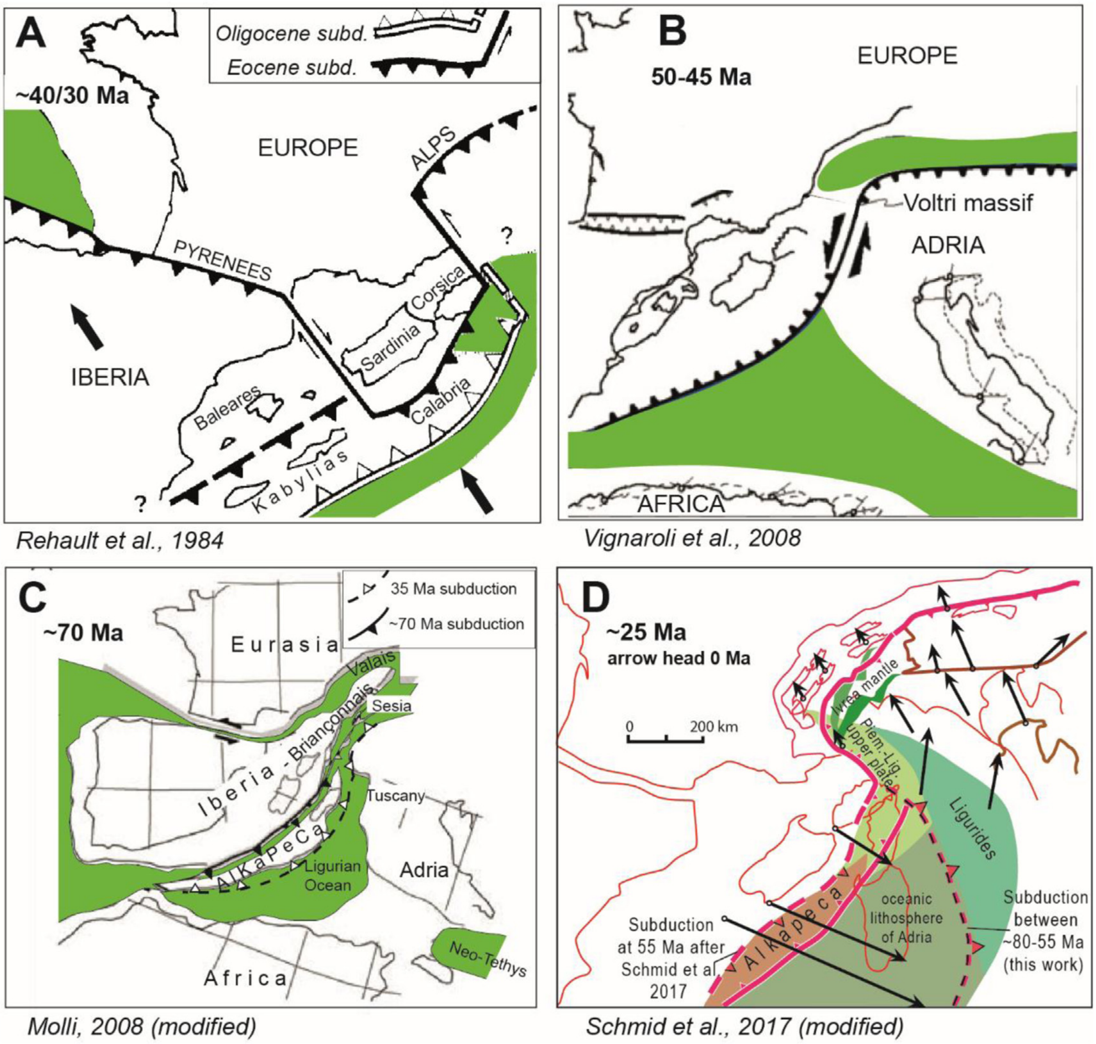
**Fig. 16.** A new proposal for the Late Cretaceous-Eocene evolution of the westernmost Tethys in the frame of the Africa-Eurasia convergence. A: Southeast-ward subduction of the Tethyan slab beneath Africa during Late Cretaceous-Paleocene times. The width of the Maghrebian Ocean is a conservative estimate intermediate between those suggested by Frizon de Lamotte *et al.* (2011) and Handy *et al.* (2010), ~200 km and ~700 km, respectively. B: After the middle-late Eocene Subduction Polarity Reversal; subduction of the slab beneath the Alkapeca orogenic arc and back-arc opening of the West-Algerian Mediterranean basin.



J. Taounart cross-section (Babors) after Obert (1974)

Reinterpretation (this work)

**Fig. 17.** Superimposed unconformities in the Babors massif (location: Fig. 11). A: Present cross-section presented by Obert (1974) as a proof of Early and Late Cretaceous folding events, involving overturned pre-Cenomanian folding. B: Restoration of two stages of the structural evolution of the area, suggesting progressive ascent of a diapir of Triassic evaporitic formations.



Rehault et al., 1984

Vignaroli et al., 2008

Molli, 2008 (modified)

Schmid et al., 2017 (modified)

**Fig. 18.** Location of the subduction zones and interpretation of the SPR during Africa-Eurasia convergence in the Western Alps-Maghrebides area. A: Early drawing by Rehault *et al.* (1984); SPR occurred along time, at about 35 Ma; B: According to Vignaroli *et al.* (2008), opposite polarities occurred contemporaneously along the plate boundary. C: After Molli (2008), the Late Cretaceous Alpine subduction occurred along the "Betic Ocean" between Iberia and Alkapeca, and the Eocene-Oligocene Apenninic subduction along the opposite border of Alkapeca. D: Schmid *et al.* (2017) retain this scenario and provide a quantification of the Oligocene-Neogene displacement of the intervening continental blocks.

(SPR) occurred between the Paleocene and the Eocene inception of the Apennine-type subduction in the Western Mediterranean area. Notice that we use here the term SPR to describe a reversal of polarity over time and along the same transect (SPR *s. str.*, *e.g.*, Fig. 16B), but some authors used it to depict opposite, although coeval polarities of subduction zones located on distinct transects of the same plate boundary (*e.g.*, Vignaroli *et al.*, 2008, Fig. 18B).

In their pioneering work, Rehault *et al.* (1984) considered that the European passive margin and adjacent oceanic lithosphere were subducting southeast-ward during the Eocene, at least from the Western Alps to south of Corsica and probably until the Alboran area (Fig. 18A). They additionally assumed that a "flip" of subduction polarity (= SPR s. str.) occurred with the onset of the northwest-dipping, southeast-retreating Oligocene subduction Later on, several authors proposed that a northwest-dipping subduction existed along southeast Iberia as early as the Late Cretaceous (Fig. 18B; *cf.* Stampfli and Marchant, 1997; Jolivet and Faccenna, 2000; Jolivet *et al.*, 2008; Vignaroli *et al.*, 2008; Frizon de Lamotte *et al.*, 2011; Rossetti *et al.*, 2022), which nourished a still vivid controversy. Most of the controversy concerned the interpretation of the complex area where the Western Alps connect with the Apennines, *i.e.*, the "Ligurian knot" (Laubscher *et al.*, 1992) between the Liguria and Corsica transects (Fig. 2). In his description of this complex area, Molli (2008) emphasized the role of superimposed orogenic stages with, i) Late Cretaceous-Eocene, east-dipping intra-oceanic then continental subduction (involving Corsica); ii) Late Eocene-Oligocene inversion of subduction polarity coeval with sinistral strike-slip due to northwestward Adria movement (Fig. 18C). In line with Michard *et al.* (2002), Molli (2008) proposed that the Late Cretaceous subduction zone extended along Iberia, which is at odds with our current restoration (Fig. 15, and sect. 4.1). Schmid *et al.* (2017) based their restoration of the Late Cretaceous paleogeography on the concept of Betic Ocean (Puga *et al.*, 2011) and placed a Late Cretaceous-Eocene SE-dipping subduction zone along the northwest margin of the Alkapeca blocks (Fig. 18D). In the latter figure, we added the location we favor for this subduction zone, *i.e.*, along the North-African margin as shown above.

### 4.4 Some pending issues

A number of topics among those presented above deserve further research, and first of all the reinterpretation of cross-sections from the Dorsale Calcaire units or from some Tell structures. These critical geological data would clearly need new field studies. Likewise, concerning the LEPMs, although bending of the lithosphere and slab pull certainly play a major role in the late extension of the Briançonnais paleomargin and the Pelagian-Sirte basin, precise quantification and modeling remain to be done. Moreover, it should be interesting to distinguish between different types of LEPMs. In the Briançonnais type, late extension mostly occurs at distance from the subduction zone. In contrast, the South China margin is affected by late extension due to a migrating forebulge close to the front of the Taiwan orogenic prism (Yu and Chou, 2011). Similarly, the Central Apennine proximal margin is bended and affected by extension when it is overloaded by the approaching Apennine accretionary prism (Carminati *et al.*, 2014).

On the other hand, the overall plate geodynamics of the area could have influenced the tectonics of the extending passive margin, as suggested by Claudel *et al.* (1997). Extensional deformation affected the upper plate of the Alpine-Maghrebian subduction zone not only in the Rif-Tell passive margin, but also in the Atlas and sub-Saharan domains until Albian-Turonian times (Zouaghi *et al.*, 2005; Herkat and Guiraud, 2006; Bouzakraoui *et al.*, 2023), just before the (moderate) compression reported in the above section. Conversely, extension affected the Delphino-Helvetic domain west of the European margin of the Briançonnais transect (Fig. 15) from the Albian to the Campanian-Maastrichtian in the Vocontian Basin (Arnaud and Lemoine, 1993; Michard *et al.*, 2010). Likewise, in the area of the future Helvetic nappes, extensional faulting was active during the Turonian-early Maastrichtian times (Cardello and Mancktelow, 2014). Opening of the Valais oceanic basin occurred during the latest Jurassic-Early Cretaceous (Loprieno *et al.*, 2010), whereas the transcurrent opening of the Pyrenees Basin is dated from the late Aptian-Cenomanian (Lagabrielle *et al.*, 2019; Angrand and Mouthereau, 2021). Finally, along the south-eastern border of Iberia, two rifted basins extended during the Late Cretaceous (Fig. 15), *i.e.*, the Valencia-Columbrets Basin, which represents a Late Jurassic-Early Cretaceous rift basin (Etheve *et al.*, 2018), and the "Betic Ocean" (Puga *et al.*, 2011) or Nevado-Filabrides OCT domain (Jabaloy-Sánchez *et al.*, 2019), which rifted during the Early Jurassic and spread until the Late Cretaceous (Turonian?) (Puga *et al.*, 2011). For a quantitative description of the mechanisms at play in the late extension of the Briançonnais-Alkapeca margin, it will be advisable to take into account this peripheral setting.

## 5 Conclusion

In this paper, we first drew attention to a character of the Briançonnais margin hitherto neglected: this distal part of the European margin kept extending from the Early Jurassic rifting stage to the Paleocene, immediately before it encroached the Alpine subduction during the Early-Middle Eocene. The Briançonnais is archetypical for a rare type of passive margins here labeled Late-Extended Passive Margins (LEPM), that keep extending as the adjacent oceanic lithosphere subducts along the opposite continental margin.

Second, we emphasized that a post-rifting extensional regime also affected the Dorsale Calcaire units of the Alkapeca blocks, which originate, like the Briançonnais, from the northwest margin of the Maghrebian Tethys. This late extension mainly occurred during the Late Cretaceous-Paleocene times in the Kabylian and Peloritan transects, but began as early as the Late Jurassic in the Alboran and Peloritan transects. We assume that the post-rifting extensional tectonics of the latter transects resulted from the sinistral kinematics of Africa relative to Eurasia during opening of the Central Atlantic and Alpine Tethys whereas the Late Cretaceous-Paleocene extension of the Kabylian-Peloritan transects can be linked to the onset of plate convergence and subduction of the

Ligurian-Maghrebian slab below North-Africa. Therefore, the well-described Eocene subduction polarity reversal operated with a shift of the subduction zone from the southern Ligurian-Maghrebian Tethys margin to the northern one.

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