The role of rift-inherited hyper-extension in Alpine-type orogens

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The role of rift-inherited hyper-extension in Alpine-type orogens

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Abstract

Alpine-type orogens are interpreted to result from the collision of former rifted margins. As many present-day rifted margins consist of hyper-extended domains floored by thinned continental crust (<10 km) and/or exhumed mantle, this study explores the influence of rift inheritance on the architecture and final evolution of Alpine-type orogens. We propose that rift-related necking zones, separating weakly thinned 25- to 30-km-thick crust from hyper-extended domains, may act as buttresses during the transition from subduction to collision. As a result, former necking zones may now be found at the boundary between a highly deformed and overthickened nappe stack, made of relics of hyper-extended domains, and an external, weakly deformed fold-and-thrust belt, which largely escaped significant rift-related crustal thinning and orogeny-related thickening. Therefore, the role of rift inheritance is of critical importance and is largely underestimated in controlling the architecture and evolution of Alpine-type orogens.

Introduction

Collisional mountain belts, such as the Alps, are commonly interpreted to result from the imbrication of rifted margins and intervening ‘oceanic’ domains (Dewey and Bird, 1970). Therefore, the formation and evolution of mountain belts is closely interlinked with the architecture of the former rifted margins. The development of high-resolution seismic imaging methods combined with drilling at deep-water rifted margins led to a paradigm shift in the understanding of the architecture and evolution of rifted margins. Most rifted margins show evidence for hyper-extension prior to lithospheric breakup. Hyper-extended domains are characterized by: (1) extremely thin continental crust and exhumed subcontinental mantle extending over hundreds of kilometres (e.g. Reston and Manatschal, 2011), and (2) necking zones marking sharp boundaries between weakly thinned crust and hyper-extended <10-km-thick crust (Osmundsen and Ebbing, 2008; Mohn *et al*., 2012). The implications of these discoveries for the evolution of collisional orogens are poorly explored (Butler, 2013; Jammes *et al*., 2014). Therefore, this study aims to discuss the importance of necking zones in controlling the architecture and evolution of the Western Alps, focusing essentially on the deep seismic ECORS-CROP section.

Hyper-extension at rifted margins: a north Atlantic perspective

The southern North Atlantic hosts a complex network of <400-km-wide hyper-extended rifts, filled by thick sedimentary sequences deposited onto severely thinned continental crust (<10 km) or exhumed subcontinental mantle (e.g. Welford *et al*., 2012) (Fig. 1). These hyper-extended basins (e.g. Galicia Interior, Porcupine, Rockall, Hatton basins) are separated by weakly thinned basement highs (Galica, Hatton, Rockall, Porcupine Banks). Seismic surveys (e.g. O'Reilly *et al*., 2006) have revealed that the transition between these basement highs and the adjacent deep-water hyper-extended basins is characterized by a rapid basinward decrease in crustal thickness from ~30 km to <10 km over a distance of 50–60 km, corresponding to the so-called ‘necking zone’ (Fig. 1). The necking zone separates low strain ($\beta < 1.5$) from hyper-extended ($\beta > 1.5$) domains. As shown by the example of the North Atlantic, most hyper-extended rift systems did not reach the breakup stage and ended up as intra-plate deep-water sedimentary basins, with local exposures of exhumed subcontinental mantle associated with MORB-type magmatism (e.g. Scrutton and Bentley, 1988).

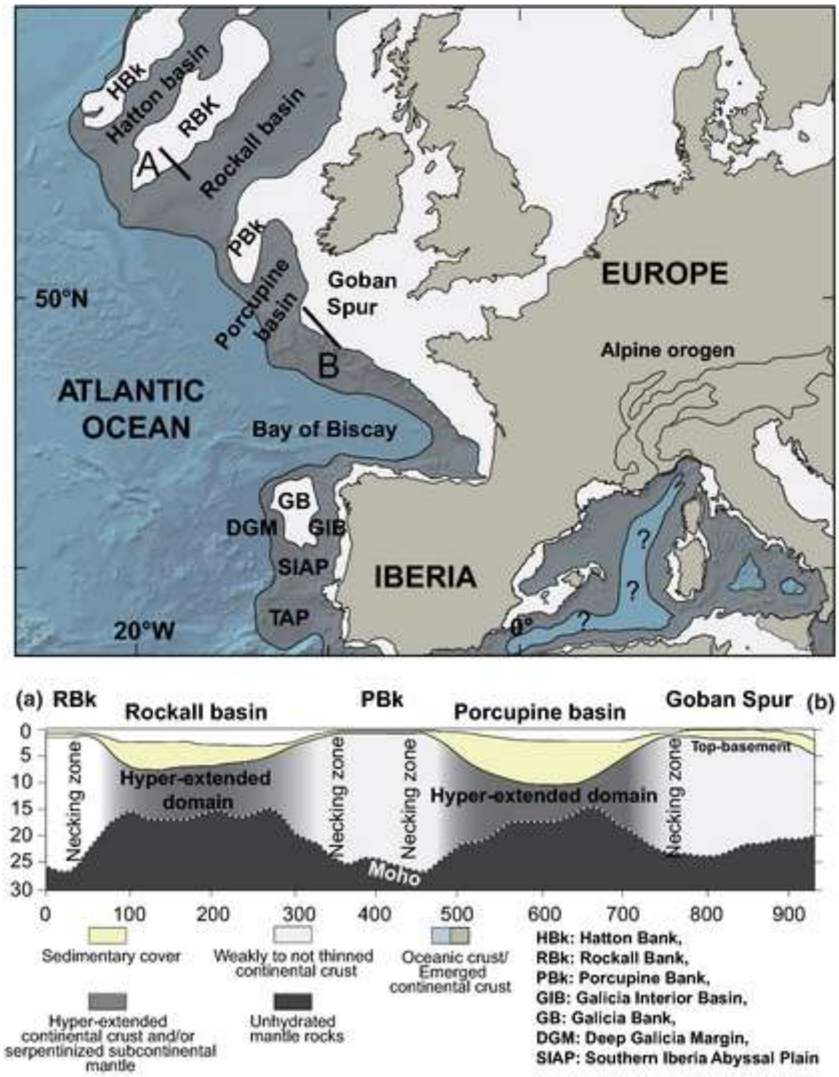

Figure 1. (a) Map of the hyper-extended domains in the Southern North Atlantic modified after Péron-Pinvidic and Manatschal, 2010 and Lundin and Doré, 2011. Bathymetry reproduced from the GEBCO world map, http://www.gebco.net/, (b) Profile across the Porcupine and Rockall basins modified after Welford *et al*., 2012 (Moho is deduced from inverted density anomaly and top basement from seismic reflection data).

Reactivation of hyper-extended domains: an Alpine perspective

Evidence for rift-related hyper-extension in the fossil Western Tethys domain sampled in the European Alps has been reported since the early 1990s (e.g. Froitzheim and Eberli, 1990; Marroni *et al.*, 1998 and references therein). Since then, the study of present-day Atlantic-type rift systems has benefited from studies of the Tethyan system (Manatschal and Bernoulli, 1999). The Alpine orogen is interpreted to result from the closure of pre-existing Mesozoic basins, including the Jurassic Western Tethys, separating the European and Adriatic plates (Frisch, 1979). The Western Tethys consisted of the Piemonte-Liguria and Valais basins separated by a basement high, referred to as the Briançonnais domain (Trümpy, 1960; Stampfli, 1993). From the Late Cretaceous onward, these basins were inverted and reactivated, leading to the Tertiary collision between the European and Adriatic plates (e.g. Froitzheim *et al.*, 1996).

Geological and deep seismic geophysical data have enabled the subdivision of the Alpine orogen into external and internal zones, imaged by long offset seismic surveys such as the ECORS-CROP project (Roure *et al.*, 1996) (Fig. 2).

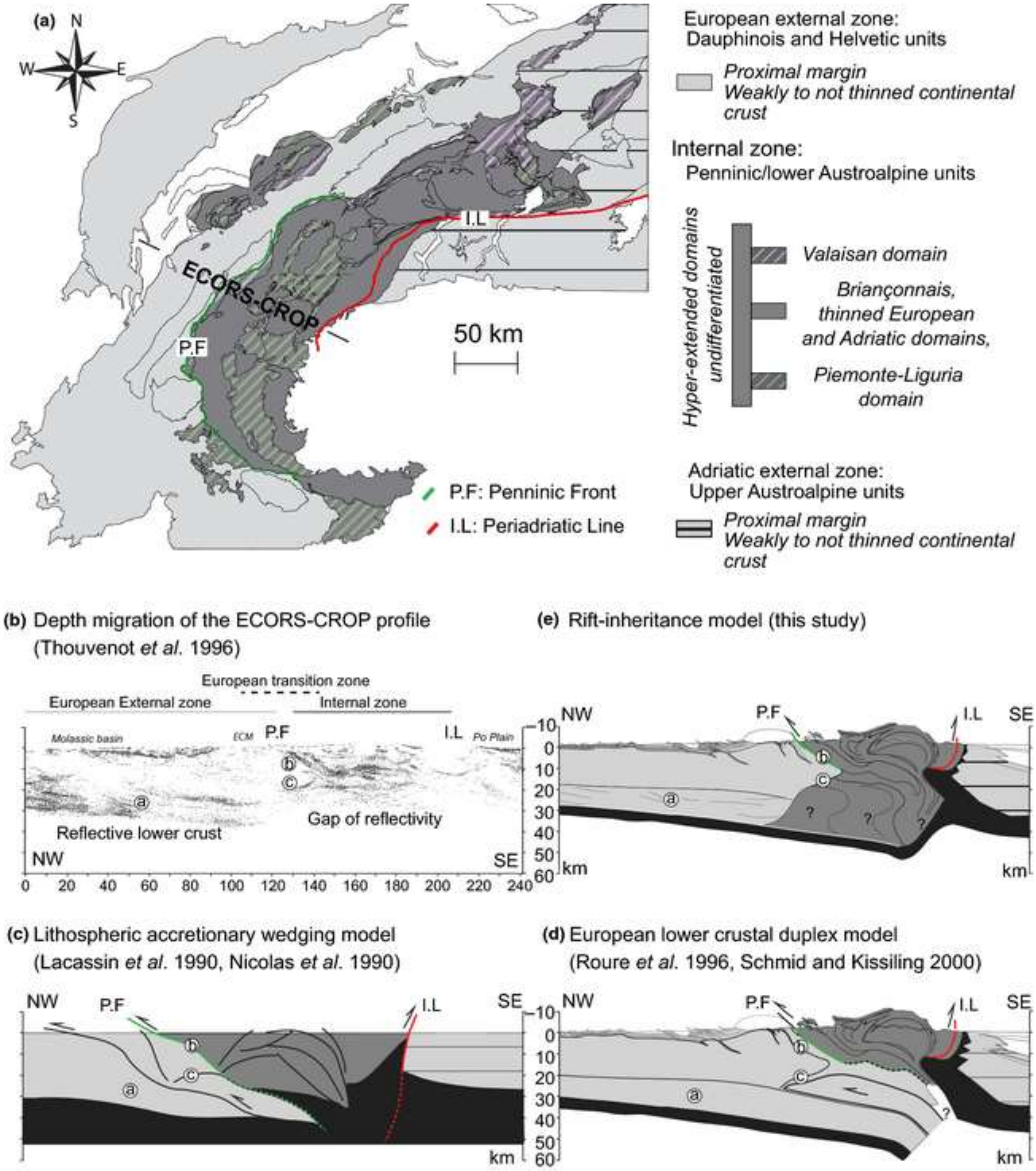

Figure 2.

(a) Simplified palaeogeographical map of the Alps. The European external zone extends from the little-deformed Jura Mountains, across the foreland Molasse basin and the fold-and-thrust belt of the Dauphinois nappes to the External Crystalline Massifs. It is separated from the internal zone by the Penninic Front (P.F). The internal zone is bounded by the P.F to the WNW and by the Insubric line to the ESE, (b) Depth migration of the ECORS-CROP profile modified after Thouvenot *et al.*, 1996. (c, d) Selected published interpretations of the ECORS-CROP profile. (c) 'Lithospheric accretionary wedging' model (Lacassin *et al.*, 1990; Nicolas *et al.*, 1990). (d) 'European lower crustal duplex' model (Roure *et al.*, 1996; Schmid and Kissling, 2000). (e) 'Rift inheritance model', which combines observations of surface geology with the geometry of present-day rifted margins. Note that the Moho drawn in our model is in good agreement with the tomographic Moho of Diehl *et al*. (2009). ECM: External Crystalline Massifs.

The External European Zone (EEZ) extends from the Jura Mountains to the External Crystalline Massifs (ECM). It is separated from the internal zone by the Penninic Front (P.F). The EEZ is characterized by a relatively constant Moho depth of ~30 km. Approaching the ECM, the present-day Moho dips slightly towards the internal zone (i.e. south-eastward) reaching a depth of ~40 km (Thouvenot *et al*., 2007). Throughout the EEZ, the lower crust is characterized by a continuous high-reflectivity pattern (Fig. 2b, point a). The EEZ was affected by a weak Alpine metamorphic overprint, reaching lower greenschist facies conditions in the footwall of the P.F (Bousquet *et al*., 2008). Alpine structures are essentially controlled by decollement horizons within the sedimentary cover, defining a classical thin-skinned fold-and-thrust-belt geometry (Butler, 1986). The external parts of the orogen reactivated low-β rift basins belonging to the former proximal margins (Lemoine and Trümpy, 1987). During the Late Jurassic to Early Cretaceous post-rift stage, this domain underwent minor thermal subsidence, as indicated by the formation of prograding carbonate platforms (Lemoine *et al*., 1986). Notably, both surface and subsurface data indicate that the EEZ escaped significant rift-related crustal thinning in the Mesozoic and orogeny-related thickening during the Tertiary.

In the internal zone of the Western Alps, geophysical data show an overthickened crust of 50–60 km (Thouvenot *et al*., 2007) (Fig. 2b). In contrast to the external zone, the rocks exposed in the internal zone are largely affected by pervasive Alpine deformation and pressure-dominated metamorphism (Ernst, 1971; see Rosenbaum and Lister, 2005 and Beltrando *et al*., 2010a for reviews). This zone consists of a complex stack of remnants of continental basement, ophiolites and disrupted sequences of pre- and syn-rift sediments overlain by continuous and thick post-rift sequences, locally grading upsection into ‘Flysch’ deposits.

The pre-orogenic structure and its relationship with the sedimentary sequences within the former distal margins are known only from domains that escaped pervasive Alpine deformation preserved in the Central Alps (e.g. Tasna, Platta/Err/Bernina nappes; Manatschal, 2004). These units preserve remnants of hyper-extended continental crust and serpentinized subcontinental mantle associated with low-angle extensional detachment systems, directly overlain by syn- to post-rift sediments. These remnants indicate local rift-related exhumation of deeper crustal and subcontinental mantle rocks associated with the delamination of crustal blocks and pre-rift cover (e.g. extensional allochthons).

Recent studies from the more deformed internal zone of the Western Alps (e.g. Beltrando *et al*., 2014) have shown that some of these units preserve the diagnostic features of remnants of pre-Alpine hyper-extended domains similar to those described in the Central Alps (Masini *et al*., 2013). Within the ECORS-CROP profile, lithological associations diagnostic of hyper-extended domains were recognized in the Valaisan (Beltrando *et al*., 2012) and the Piemonte-Liguria units (Dal Piaz, 1999; Beltrando *et al*., 2010b).

Along the ECORS-CROP profile, the transition between the external and the internal zones is marked by the regional P.F (Schmid and Kissling, 2000; Ceriani *et al*., 2001). At depth, this transition corresponds to: (1) an abrupt termination of the strongly reflective European lower crust, well imaged beneath the external zone (reflections at 25–30 km depth), and (2) the occurrence of a complex band of sub-horizontal reflections beneath the internal zone (Fig. 2). This change in the seismic nature is most likely indicative of variations in the rock associations and structures along this transition zone. Significantly, the abrupt disappearance of the lower crustal reflectivity coincides with the appearance of a strong NW-dipping intracrustal reflector that does not surface (Fig. 2b, point c). At the surface, instead, the P.F corresponds to ESE-dipping reflectors visible down to 15 km (Schmid and Kissling, 2000) (Fig. 2b, point b). We suggest that these NW- and ESE-dipping reflectors, which bound a wedge-shaped crustal body, mark the SE-ward limit of the 'thick' continental crust belonging to the former European proximal margin.

At the surface, these ESE-dipping reflections (e.g. P.F) mark the boundary between (1) Upper Jurassic to Lower Cretaceous shallow marine platform sediments (Dauphinois domain) associated with long-lived post-rift topography, in the footwall, and (2) a continental escarpment grading into areas locally floored by exhumed subcontinental mantle, both sealed by deep-water sediments in the Valaisan basin, in the hangingwall ('Valais trilogy', Loprieno *et al*., 2011 and references therein). These different lithostratigraphic associations indicate that, along the P.F., a weakly deformed 25- to 30-km-thick crust derived from the former European proximal margin is directly juxtaposed against a pre-orogenic hyper-extended domain, including windows of exhumed mantle, now found in the overthickened internal parts of the Alps.

Control of rift-inherited hyper-extension on the Alpine orogeny: the role of the necking zone

Starting in the Late Cretaceous, the hyper-extended domains of the Western Tethys were subducted underneath the Adriatic plate (Fig. 3) partly exhumed and stacked within the internal parts of the present-day Alps (e.g. Dal Piaz *et al*., 2001; Beltrando *et al*., 2010a). Following the subduction of the hyper-extended domains (e.g. Dal Piaz *et al*., 2001) and Brianconnais high (e.g. Lanari *et al*., 2013), the European proximal margin became involved in continental collision, during the late Eocene–early Oligocene (Fig. 3) (e.g. Schmid *et al*., 1996). Deformation propagated and developed along a pro-fold-and-thrust belt over the EEZ, while synorogenic deposits evolved from 'Flysch' to 'Molasse' type sedimentation (e.g. Ford *et al*., 2006; Dumont *et al*., 2012). This major switch in the orogenic evolution records the change from a subduction to a collisional stage. It is important to note that the onset of collision post-dates the subduction of the hyper-extended crust but coincides with the involvement of the proximal margin, with a thicker continental crust, in the subduction. The switch from a subduction to a collisional stage may therefore correspond to the moment when the necking zone starts to get involved in the subduction. As a result, it appears that the European necking zone acted as a buttress during the Alpine collision. The scenario proposed here accounts for the observed sharp transition between the EEZ, only weakly affected by rift-related thinning and subsequent orogenic-related thickening, and the internal zone, where hyper-extended domains underwent extensive reworking during Alpine subduction/orogeny. Large parts of the European hyper-extended domains may have been underthrust/subducted, as indicated by the strong metamorphic overprint of the Lower Penninic Units in the Central Alps (Berger and Bousquet, 2008).

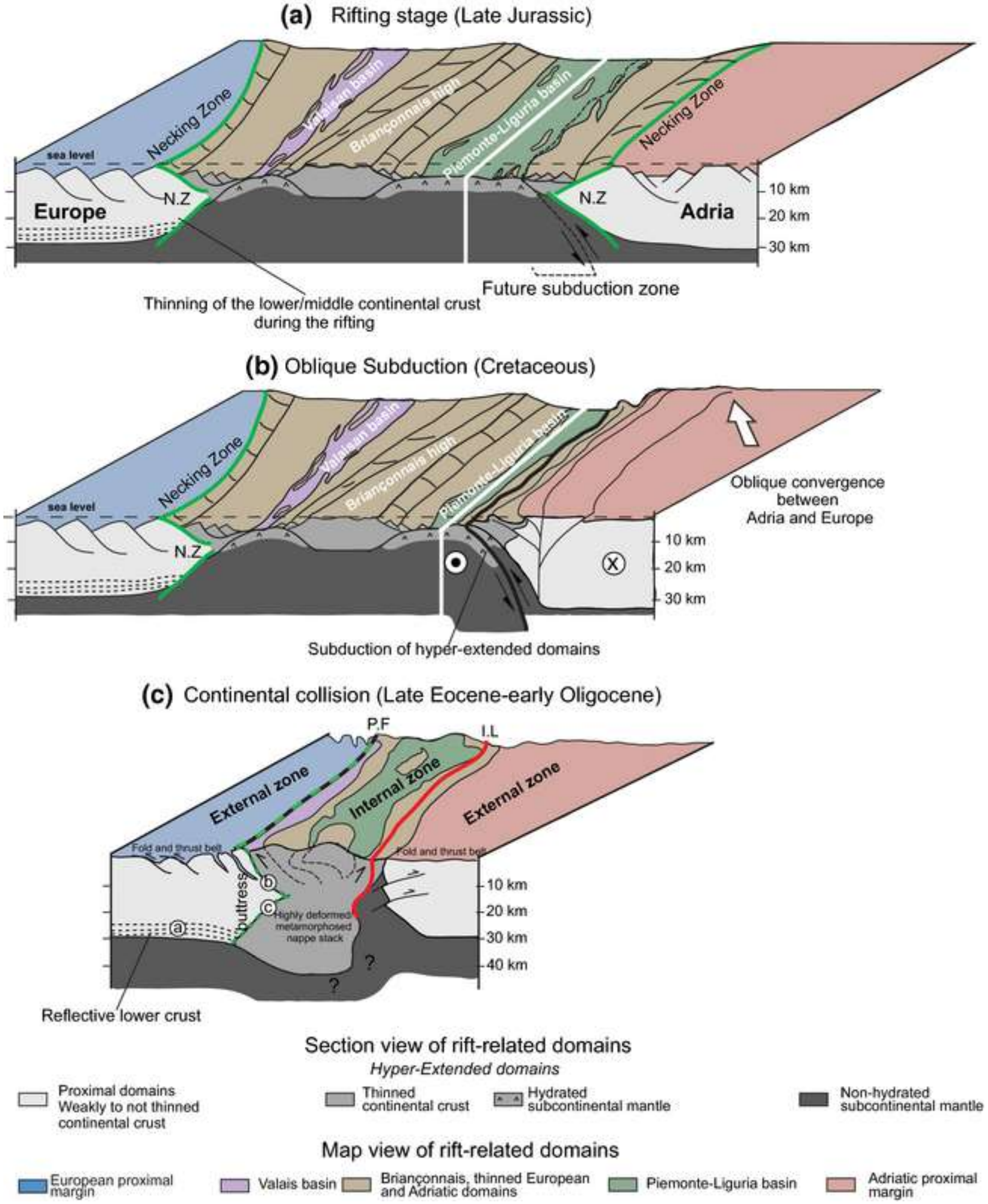

Figure 3.

Conceptual model illustrating the role of rift-inherited hyper-extension in the architecture of the Alps. (a) Rifting stage, (b) Subduction stage, (c) Continental collision stage. It is important to note that subduction of the Piemonte-Liguria basin, which probably consisted of hyper-extended rifted margins bounded by transform faults, took place within a setting characterized by highly oblique convergence (Beltrando *et al*., 2010a).

Implications/conclusions

Many different interpretations have been proposed for the ECORS-CROP profile (Fig. 2) (Lacassin *et al*., 1990; Nicolas *et al*., 1990; Roure *et al*., 1996; Schmid and Kissling, 2000). Most of these interpretations assumed that the entire length of continental crust involved in the orogeny had to be restored back to a presumed initial thickness of ~25–30 km to balance the pre-collisional cross-section. Consequently, these restorations require the existence of continuous European crust below the Alpine root (Fig. 2c,d). In this context, the 'missing' continental crust, necessary to restore the crust back to ~25–30 km, is interpreted either to form the roots of the Alpine orogen or to be part of the subducted slab. These interpretations neglected the possibility that parts of the European margin consisted of extremely thinned continental crust within a hyper-extended domain located offshore of a necking zone.

In Fig. 2e, we propose a re-interpretation of the ECORS-CROP profile based on the established analogies between the Alpine and present-day rifted margins (e.g. Manatschal and Bernoulli, 1999). As argued in the previous sections, considerations based on the type of Mesozoic cover and basement indicate that the internal zone of the Western Alps and the EEZ originated from distinct rift-related palaeogeographical domains of different crustal thickness. We suggest that, at a first order, the extent of reactivation and inversion of these rift domains within the orogen is a direct consequence of their pre-orogenic architecture and crustal thickness.

Moreover, the location of the P.F, a regional Alpine tectonic contact, corresponds to a major rift-related boundary between hyper-extended and proximal domains of the European margin. Therefore, the disappearance of the highly reflective European lower crust below the south-eastern edge of the EEZ in the ECORS-CROP profile is ascribed to crustal thinning during Jurassic rifting, rather than to Alpine convergence (e.g. Nicolas *et al*., 1990 Fig. 2c or Schmid and Kissling, 2000 Fig. 2d, and 3). We propose that reflections b, identified as the P.F, and c in the ECORS-CROP profile correspond to the former necking zone of the European margin and are inherited from Jurassic hyper-extension in the Western Tethys.

In contrast to previous interpretations proposing the presence of European lower crust at the base of the Alpine root, we suggest that this zone is formed of relics of the former Valais, Briançonnais and Piemonte-Liguria hyper-extended domains. In the case of the ECORS-CROP profile, the Alpine root might also consist of European hyper-extended crust/exhumed subcontinental mantle and related sediments (e.g. Middle/Lower Penninic units). Relics of this domain crop out further to the NE in the Central Alps, but are not found at the surface along the ECORS-CROP profile in the Western Alps. This interpretation is in accordance with recent results from the Southern Range of Taiwan, where the accretionary prism is mainly built from a large volume of underthrust hyper-extended crust (McIntosh *et al*., 2013).

If rift-related structures such as necking zones and hyper-extended domains are considered in restorations, the amount of shortening within the Alpine orogen established by classical restorations or balanced cross-sections diminishes considerably. Indeed, different reconstructions of the European domain have been proposed requiring either several major crustal-scale shear zones (i.e. P.F) delaminating the entire crust with major offsets (e.g. Lacassin *et al*., 1990) or local inversion of rift basins in the upper crust associated with a relatively moderate amount of shortening (e.g. Dumont *et al*., 2008). As shown in our preferred interpretation of the ECORS-CROP profile, the EEZ, including the ECM (i.e. proximal rifted margin), probably acted as a buttress during collision. This interpretation would imply that much less shortening was accommodated in the European foreland during the final evolution of the external parts of the Alps than is commonly suggested.

It is important to note that the Alpine Tethys system was a relatively narrow rift system, which did not exceed 400–600 km in width (Rosenbaum and Lister, 2005). This size is comparable with the hyper-extended rift basins of the North Atlantic (e.g. Porcupine or Rockall basins; Fig. 1). These basins, which are some hundreds of kilometres wide, show well-developed necking zones associated with hyper-extended domains and local mantle exhumation. Importantly, all these rift systems failed to evolve into a stable plate boundary. This observation might be important in the context of the Western Alpine Tethys, considering that unambiguous evidence for the existence of a wide, mature oceanic domain is still missing in the Alps (Manatschal and Müntener, 2009). Therefore, the possibility that the Alps developed from the reactivation of hyper-extended domains, and are thus not representative of 'typical' long-lived subduction systems involving wide oceanic domains, should be taken into account.

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