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Perspective

Extension in Alpine Western Europe and West Mediterranean

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Quite recently, the geological description of a restricted zone of the Peloritani Mountains of northeastern Sicily appeared in *Comptes rendus Geoscience* [46]. Indeed, the cited paper documents the first evidence for synorogenic extension in this segment of the Alpine orogen, and thus ranks among the many recent works that deal with extensional tectonics in Alpine Western Europe and West-Mediterranean areas. Within this large domain, Tertiary extensional tectonics is evidenced in two different settings, i.e., on the one hand, the Pyrenean-Alpine foreland, and, on the other hand, the Alpine belts themselves.

First, Tertiary extension is responsible for the development of a major, NNE-trending rift system (Fig. 1), referred to as the European Cenozoic Rift System (ECRIS), with both onshore parts (Rhine graben, Limagnes, etc.) and offshore parts (Gulf of Lion, Valencia Trough, etc.). The onshore ECRIS extends in 'stable Europe', but its southern, offshore continuation affects large parts of the Pyrenean–Alpine belt itself (eastern Pyrenees, southwestern Alps, Betic Cordilleras, etc.). Remarkably, these extensional structures developed contemporaneously with the youngest stages of the Alpine orogenesis, and in the framework of ongoing Africa–Europe plate convergence. Some decades ago, there was a tendency to consider extensional tectonics as independent from the opposite, compressional one, and thus the model of abnormal mantle/plume-related active rifting was generally preferred [34]. Since then, the coupling of rifting and plate convergence was clearly recognized following different scenarios such as collisional foreland splitting (e.g., [10,11], with references therein), forebulge flexural bending [47], back-arc spreading and slab roll-back [15,21,24,38,44], or slab-pull [29,32].

Second, the close association of extension and shortening within the collisional belt itself during orogenesis was recognized in the Alps, particularly in the Tauern and Simplon culminations, and the western Alps [2,18,30,35,51], the Betic Cordilleras [20,25,36], and Calabria [43,49]. This was interpreted, either in relation with lateral escape of the compressed belt (orogen-parallel extension), or by gravity-driven collapse of the thickened orogenic prism (orogen-perpendicular extension). On the other hand, extensional structures may also accompany extrusion of buoyant metamorphic rocks in the subduction channel, resulting in 'relative extension' (ductile normal shear) with respect to the rigid hanging-wall [14,22]. Such varied synorogenic/late orogenic extensional processes are crucial for the exhumation of high-pressure, low-temperature (HP–LT) metamorphic rocks. Back-arc rifting may immediately follow, and take advantage of these intra-orogenic extensional processes, which is perfectly illustrated in the Alboran domain. There, the Alpujarride–Sebtide units of the Betic Rif orogen evolved through alternating compressional–extensional deformations during the Late Palaeogene [3,6,9] before being definitely exhumed during the Late Oligocene–Early Miocene Alboran rifting, and then folded and uplifted (up to 3000 m in the Sierra Nevada [19,26]) or drowned beneath the Alboran Sea [5,8,20] during the Neogene. The quoted paper by Somma et al. [46] illustrates a closely similar example from the Peloritan–Calabrian Arc, which is the eastern homologous of the Betic-Rif, or Gibraltar Arc.

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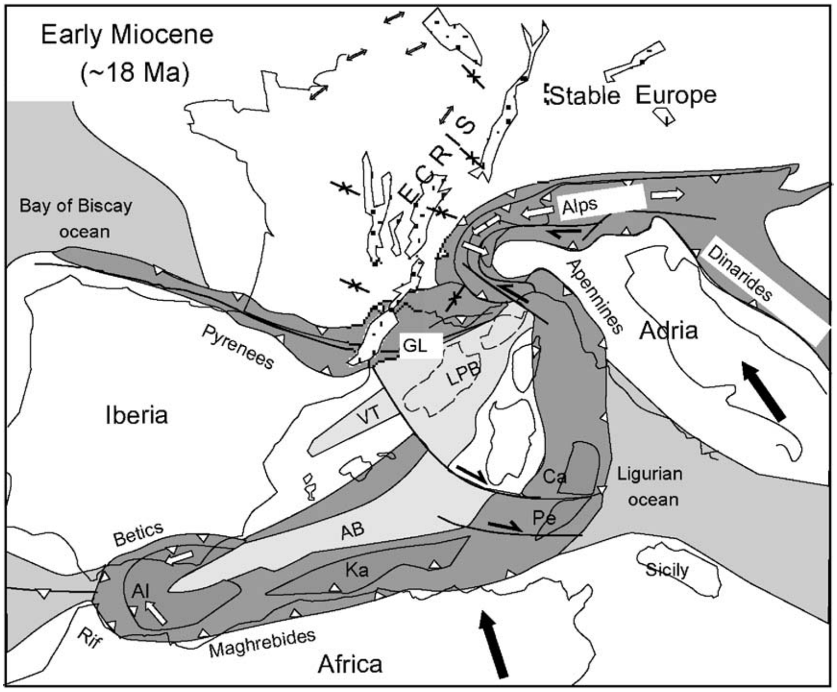

Fig. 1. Early Miocene palaeotectonic sketch map of ECRIS and West-Mediterranean areas, after Michard et al. [31] and Dèzes et al. [11]. Legend: dark grey: orogens; light grey: areas of young oceanic or thinned continental crust; stippled: intracontinental rift system; large black arrow: Africa–Europe convergence; small facing black arrows: maximum horizontal stress direction; white arrows: Neogene extension in the Internal Alps [7,18]; light grey arrows: extensional stress in the northwestern Alpine foreland [40]. Al: Alboran; AB: Algerian-Balearic basin; Ca: Calabria; GL: Gulf of Lion; Ka: Kabylias; LPB: Ligurian–Provençal basin; Pe: Peloritani Mountains.

The balance between extension and compression (shortening) during the late orogenic stages was repeatedly questioned in the western Alps, a belt where high-grade HP–LT (eclogite-facies) and ultra-high-pressure (UHP) rocks are widely exposed, and which, however, escaped such an intense rifting evolution as the West-Mediterranean domain. The role of early 'relative extension' in the subduction channel as a mechanism for the early exhumation of eclogite-facies/UHP rocks has been emphasized [1,22,30]. However, the widespread effects of late orogenic extension were clearly recognized through structural field studies of active and recent faults, seismic analysis of focal mechanisms, and geodesy, including GPS measurements (see [7], with references therein). At the base of the northwest-verging Dent-Blanche thrust nappe, late top-to-the-southeast deformation is coincident with (late) eclogite exhumation, and relevant to gravity-driven crustal extension [37]. Likewise, the Penninic Front has been inverted, i.e. this major thrust was changed into a normal fault [4,48]. In spite of the permanent Africa–Europe convergence, the internal Alps have undergone widespread extensional deformation during the Neogene, evolving from early, orogen-parallel extrusion to late and ongoing orogen-perpendicular spreading [7].

A warm controversy currently concerns the ECRIS development onshore [12,32]. Whereas Merle and Michon [29], Michon et al. [33] and Michon and Merle [32] advocate a slab-pull model, Dèzes et al. [11,12] come to the conclusion that the onshore parts of ECRIS evolved by passive rifting in response to collisional foreland splitting. The latter authors particularly argue that the Ligurian–Piemontese (Upper Penninic) oceanic slab was detached from the European lithosphere in the course of the Late Eocene, and then that slab-pull forces relaxed at the very moment when the onset of ECRIS evolution occurred. They also emphasize that volcanic activity in the ECRIS area started during the Palaeocene, reflecting the activation of a mantle upwelling system beneath the Alpine foreland. This mantle anomaly gave rise to discrete mantle plumes, imaged by seismic tomography, and caused thermal weakening of the foreland lithosphere, thus rendering it prone to deformation [52]. Additionally, flexural bending at the outer bulge of the Valaisan subduction likely played an important role in the ECRIS formation [47]. By contrast, evolution of the Gulf of Lion–Valencia Trough rift system, forming the offshore extension of ECRIS, was controlled by back-arc extension related to roll-back of the Ligurian slab [39,45]. The latter process was in fact responsible for the opening of all West-Mediterranean basins [15,21,27,28,41,50], as well as of the late orogenic evolution of the associated Alpine belts [4,13,16,17,23,43]. The mechanisms at work within the overthickened crust (e.g., in the Corsica–Ligurian transect) during extension evolve from ductile, with formation of core complexes, to brittle, with rigid block faulting, crustal separation, and formation of new oceanic crust [42].

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