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# Structural and kinematic relationships between Corsica and the Pyrenees-Provence domain at the time of the Pyrenean orogeny

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[1] The Pyrenees-Provence belt and the Alps were both active in the late Eocene. Alpine Corsica was once a part of the Alps, and the now obducted metamorphic oceanic domain is similar and easily correlated in both areas. Tectonic reconstructions before the Oligo-Miocene opening of the Liguro-Provençal basin show that at the same time, Corsica was located in the hinterland of the Provençal ranges. A late Eocene cross section running from Alpine Corsica to Provence gives an image of a complete mountain belt from an internal domain made of metamorphosed oceanic material (Alpine Corsica) to the foreland fold and thrust with a thin-skinned geometry (Provence). During the late Eocene the intervening basement of western Corsica was thus within this mountain belt, probably thrust onto the European basement. We analyze and interpret the structural pattern and the overall geometry of the Provençal-Corsican domain during late Eocene times in terms of oblique convergence and strain partitioning, within the framework of the Africa-Eurasia convergence. This evolution is integrated in a set of kinematic reconstructions of the western Mediterranean region from 65 Ma to the present.

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## 1. Introduction and Scope of the Study

[2] Intersecting mountain fronts may lead to complex geometry and kinematics. The case of the Pyrenees and the Alps shows the example of an inverted rift once oblique to the main Liguro-Piemontais ocean but now closed. The situation is further complicated by the Oligo-Miocene back arc opening of the Liguro-Provençal basin related to the north dipping subduction of Africa below Eurasia, which interrupts the Pyrenees to the east and obscures the connection with the Alps. However, Alpine Corsica is a witness of the Alps rifted apart from the mainland of Europe which can be connected with the Pyrenees through Provence in the late Eocene. Despite many efforts [e.g., *Stampfli*, 1993; *Stampfli et al.*, 1998] the eastward termination of the so-called Pyrenean belt and its connection to the Alps in the Corsica-Sardinia area during the late Eocene are not unambiguously solved. We discuss in this paper the late Eocene geometry and kinematics of the Provence-Corsica area on the basis of the observation that the Provençal ranges were in the foreland of Alpine Corsica before the rifting of the Liguro-Provençal basin.

[3] The Pyrenees-Provence belt formed in Eocene times in response to the collision between the European plate and the Iberian-Sardinian-Corsican block [*Arthaud and Séguret*, 1981], within the framework of the Africa-Eurasia convergence [*Dercourt et al.*, 1986; *Le Pichon et al.*, 1988]. The Pyrenees show a prominent bend in SE France, in the area of the Corbières [*Mascle et al.*, 1994], and extend farther east in Provence (Figure 1). Oligo-Miocene extension in the west European rift (Figure 1) and the Liguro-Provençal basin and related rifting of the Gulf of Lion–Provençal margins (see *Gorini et al.* [1994], *Chamot-Rooke et al.* [1999], and *Séranne* [1999] for reviews) concealed part of the Pyrenean belt, thus truncating the structural continuity between the Pyrenees and Provence. Extensional structures superimposed obliquely onto the Pyrenean fold-thrust belt when the Corsica-Sardinia block was rotated counterclockwise while rifted (32–21 Ma) then drifted (21–15 Ma(?)) away from the Provençal coastal area [*Burrus*, 1984; *Pascal et al.*, 1993; *Chamot-Rooke et al.*, 1999; *Gattacceca*, 2001].

[4] Although structural, petrographic, and paleomagnetic evidence unambiguously supports a pre-Oligocene fit of the Corsica-Sardinia block with Languedoc and Provence (see *Westphal et al.* [1976] for a review), controversies on the timing, amount, and rate of Oligo-Miocene rotation have given rise to a number of kinematic reconstructions (see discussions by *Chamot-Rooke et al.* [1999], *Gattacceca* [2001], and *Speranza et al.* [2002]). One of the most recent reconstructions [*Gattacceca*, 2001] based on paleomagnetism suggests that most of the Corsica-Sardinia rotation occurred during the postrift period (50°–60° for Sardinia and 40°–50° for Corsica during drifting), in agreement with the work by *Gueguen* [1995]. In contrast, the question of the structural and kinematic relationships between the Corsica-Sardinia block and the Languedoc-Provence area at the time of Eurasia-Iberia collision has received little attention. The fit of the Corsica-Sardinia block with Languedoc and Provence before the rifting of the Liguro-Provençal basin supports the Provençal ranges being in the foreland of Alpine Corsica during the late Eocene, but the Pyrenean and Alpine histories of Corsica have up to now most often been considered independently. Corsica, as a part of the

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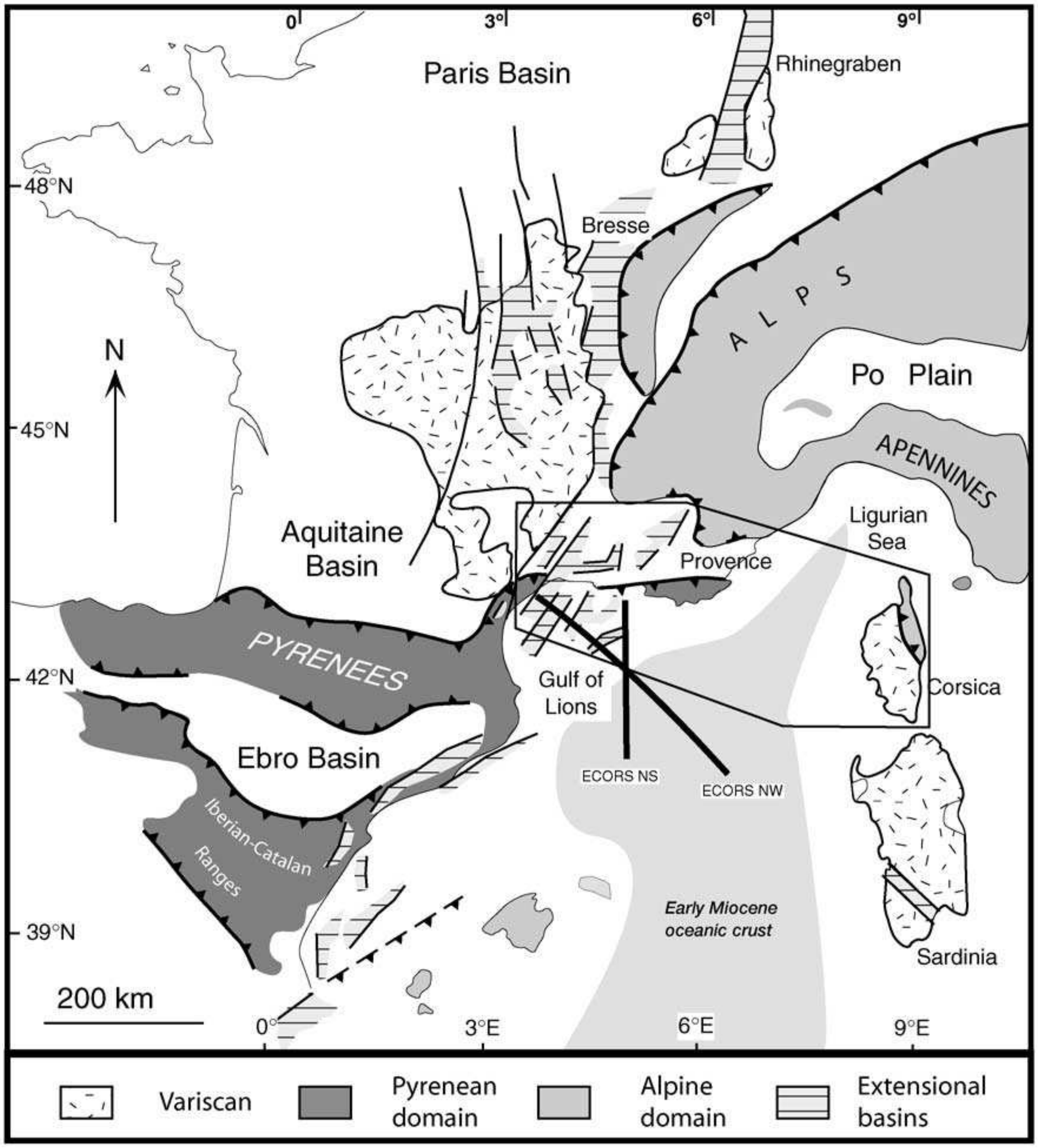

**Figure 1.** Tectonic setting of Corsica and Provence. The enclosed region indicates the investigated area. The thick black lines indicate location of the Etude Continentale et Océanique par Reflexion et Refraction Sismique (ECORS) seismic lines.

Alpine domain, was dominated by Late Cretaceous to late Eocene formation of an oceanic to continental accretionary complex thrust onto the Hercynian basement and the associated high-pressure/low-temperature (HP/LT) metamorphism [*Mattauer et al.*, 1981; *Fournier et al.*, 1991; *Caron*, 1994]. This Alpine evolution stopped in the Oligocene when postorogenic extension started [*Jolivet and Faccenna*, 2000]. On the other hand, Corsica is classically involved in kinematic reconstructions as part of the pre-Oligocene Pyrenean domain without addressing the question of the coeval Alpine evolution.

[5] This point deserves particular attention because in late Eocene times, i.e., prior to rotation, Alpine Corsica was located close to (or even within) the present-day Provençal domain, at the intersection between the E-W trending Pyrenean-Provençal orogenic front and the western Alpine orogenic front and probably close to the Africa-Eurasia subduction boundary. Following a previous attempt [*Vially and Trémolières*, 1996], this paper aims to establish that Corsica and Provence were both parts of a late Eocene "Pyrenean-Alpine" belt. To this respect, we propose a palinspastic crustal-scale cross section through this belt

which highlights its overall architecture and its rough Alpine-type organization but which also meets the difficult problem of the past location and subsequent removing of the expected underlying crustal root. This paper additionally proposes a new simple kinematic scenario involving strain partitioning in order to reconcile Pyrenean and Alpine late Eocene tectonics in this area within the kinematic framework of Africa-Eurasia convergence and compares this scenario with previous paleotectonic reconstructions.

## 2. Brief Review of Previous Kinematic Reconstructions of the Western Mediterranean

[6] The early reconstructions by *Dercourt et al.* [1986] and by *Le Pichon et al.* [1988] were devoted to the whole Tethyan realm and do not show details in the Corsica-Provence region. *Dewey et al.* [1989], on the basis of a revised plate kinematic framework for the Africa-Eurasia convergence, proposed a quite detailed scenario focused on the period spanning from 38 Ma to the present. A succession of papers by G. Stampfli and coworkers show a detailed evolution of the Alpine region from the Permian to the Late Cretaceous [*Stampfli et al.*, 1998, 2002; *Stampfli and Borel*, 2002]. These papers show the whole Tethyan region and some details on the Mediterranean evolving mostly during the Mesozoic. *Stampfli et al.* [1998, 2002] further show a zoom of the Alps-Pyrenees junction for the middle Eocene and late Oligocene, but these reconstructions are not at the same scale as the larger-scale reconstructions and consequently make any check and comparison difficult. The main hypothesis in these papers is to consider the Briançonnais domain to be rigidly linked to the Iberian plate and the Valais ocean to continue between the Briançonnais and the Dauphinois as far south as the southern Alps and between Corsica (belonging to the Briançonnais) and Provence. This hypothesis contrasts with that of *Lemoine et al.* [2000] where the Valais ocean was limited to the south by a paleotransform and did not connect to the Pyrenean rift through an oceanized domain between Provence and Corsica.

[7] *Schettino and Scotese* [2002] show reconstructions of the whole Tethyan realm based on a revision of the global plate motion model from 170 to 67.7 Ma. *Wortmann et al.* [2001] analyze various possible configurations of the paleopositions of Apulia and come to the conclusion that Apulia was rigidly linked to Africa during most of the convergence process, sharing the conclusion of *Van der Voo* [1990]. Recently, on the basis of a revision of the kinematic parameters of Africa and Iberia relative to Europe, *Rosenbaum et al.* [2002a, 2002b] proposed a detailed evolution of the western Mediterranean region from the Oligocene onward, and *Jolivet et al.* [2003] showed a succession of reconstructions which span the Tertiary of the whole Mediterranean region on the basis of the Africa-Eurasia kinematics given by *Dewey et al.* [1989]. Both works follow the general scheme proposed by *Lonergan and White* [1997] for the evolution of the Betic-Rif-Apennines orogen with a divergent retreat of the same slab toward the west and east.

[8] As can be seen through this short review of available reconstructions, no detailed work spans the concerned period from the Late Cretaceous–Paleocene to the Recent with details around Eocene times. The exception is the work of *Séranne* [1999], who proposed a detailed scenario of the evolution of the junction between the Alps and the Pyrenees from the middle-late Eocene to the present but without any information on the kinematic parameters.

## 3. What Do We Know About Late Cretaceous to Oligocene Tectonic Evolution of Provence and Corsica?

### 3.1. Structure and Late Cretaceous to Oligocene Tectonic Evolution of the Pyrenean Belt in Provence

[9] The structure of the Pyrenees is well constrained by Etude Continentale et Océanique par Reflexion et Refraction Sismique seismic profiles [*Choukroune*, 1989; *Roure et al.*, 1989, 1996] (see also a recent synthesis by *Vergés et al.* [2002]). This collision belt displays a deep asymmetric structure resulting from the underthrusting of the Iberian continental lithosphere below the Eurasian mantle indenter. A major decoupling occurs at the crust-mantle boundary of the subducting lithosphere: Part of the shortening was accommodated within the underthrust Iberian plate where deep crustal thickening led to the development of a 50 km thick crustal root; the remaining part of the shortening was balanced by major backthrusting on top of the indenter, thus designing a lithospheric-scale triangle structure. The resulting surficial structure consists of an asymmetric double-verging crustal wedge, with the elevated axial part of the Pyrenees belt flanked on its Iberian side by an E-W trending, south verging fold-thrust belt and on its French side, i.e., north of the North Pyrenean Fault (NPF) [*Choukroune and Mattauer*, 1978] by an E-W narrower, north verging fold-thrust belt, both made of allochthonous cover and basement units. The Ebro and Aquitaine foreland basins developed south and north of the Pyrenees, respectively. Estimates of shortening from crustal balanced cross sections in the Pyrenees range from 100 [*Roure et al.*, 1989] to at least 150 km in the central Pyrenees [*Munoz*, 1992; *Fitzgerald et al.*, 1999], with a decreasing amount of shortening from east to west [*Seguret and Daignieres*, 1986]. These estimates are comparable to approximately 150 to 160–170 km of total convergence between Iberia and Europe deduced from kinematic reconstructions since anomaly 34 [*Olivet*, 1996; *Rosenbaum et al.*, 2002a, 2002b].

[10] The structure of the eastern (Languedoc-Provence) segment which results from the collision between the Corsica-Sardinia block and Eurasia [*Arthaud and Séguret*, 1981] is less well constrained, as most of the belt now lies under the Liguro-Provençal basin with only the northern foreland thrust belt exposed (Figure 2). The asymmetrical structure of the Pyrenees with a wide south verging foreland thrust belt changed eastward to a wider north verging deformed area in Provence. The flexural evolution of the Provence area was marked by the accumulation of 3–4 km thick Late Cretaceous marine to fluvio-deltaic and lacustrine sediments [*Debrand-Passard and Courbouleix*, 1984] evolving into continental Paleocene-Eocene deposits in the northern part of Provence (as in the Cengle Plateau just

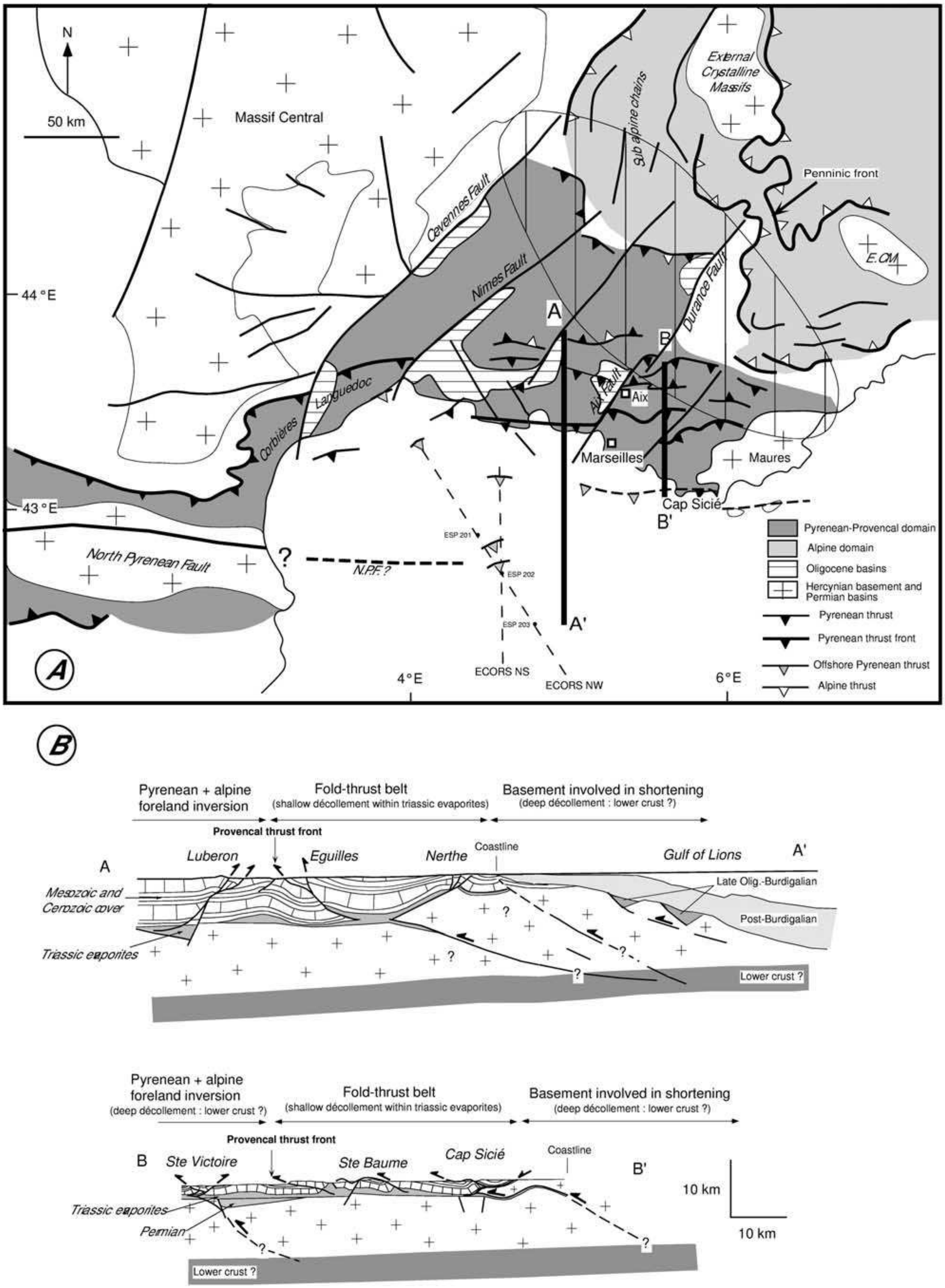
A
N
50 km
Massif Central
Cevennes Fault
Nimes Fault
Sub alpine chains
External Crystalline Massifs
Penninic front
E.CM
Durance Fault
Aix Fault
Aix
Marseilles
Maures
Cap Sicié
Languedoc
Corbières
North Pyrenean Fault
N.P.F. ?
?
44 °E
43 °E
4°E
6°E
ESP 201
ESP 202
ESP 203
ECORS NS
ECORS NW
A
A'
B
B'
Pyrenean-Provencal domain
Alpine domain
Oligocene basins
Hercynian basement and Permian basins
Pyrenean thrust
Pyrenean thrust front
Offshore Pyrenean thrust
Alpine thrust
B
Pyrenean + alpine foreland inversion
Fold-thrust belt (shallow décollement within triassic evaporites)
Basement involved in shortening (deep décollement : lower crust ?)
Provencal thrust front
Luberon
Eguilles
Nerthe
Coastline
Gulf of Lions
Mesozoic and Cenozoic cover
Triassic evaporites
Late Olig.-Burdigalian
Post-Burdigalian
Lower crust ?
Pyrenean + alpine foreland inversion (deep décollement : lower crust ?)
Fold-thrust belt (shallow décollement within triassic evaporites)
Basement involved in shortening (deep décollement : lower crust ?)
Provencal thrust front
Ste Victoire
Ste Baume
Cap Sicié
Coastline
Triassic evaporites
Permian
Lower crust ?
10 km
10 km

**Figure 2**

south of the Sainte-Victoire range), reflecting the end of the foreland basin history. However, unlike the south Aquitaine foreland basin on the northern side of the Pyrenees the foreland of the Provence segment is diffuse and poorly defined, mainly because superimposed Pyrenean and Alpine shortenings caused widespread within-plate structural inversion of Paleozoic and Mesozoic basins [*Roure and Colletta*, 1996] which prevented typical foreland flexural evolution during the Cenozoic (Figure 2a). In a more general way the complex array of multidirectional compressional structures in Provence reflects both the control by inherited structures and the geometric and kinematic complexity induced by the intersection of oblique orogenic fronts.

[11] In Provence (and Languedoc) the so-called "Pyrenean" shortening occurred from the late Senonian to the late Eocene [e.g., *Arthaud and Séguret*, 1981; *Tempier and Durand*, 1981; *Tempier*, 1987; *Lacombe et al.*, 1992; *Séranne et al.*, 1995]. In places, Pyrenean shortening is even recorded within the early Oligocene, as in Languedoc (St. Martin de Londres basin [*Philip and Mattauer*, 1978]). It is marked by folds associated with deposition of synkinematic breccia (Campanian, Dano-Montian, and Cuisian) and major thrusts. Deformation in Provence therefore correlates well in time with tectonic/erosional events related to the Pyrenean shortening identified westward in the Aquitaine basin [*Sztràkos et al.*, 1997, 1998; *Rocher et al.*, 2000], which indicates major events during the Ypresian, Ypresian-Lutetian, and late Bartonian-Priabonian and minor events during the Maastrichtian, the middle Thanetian, and the late Thanetian. Deformation in Provence also correlates well with estimates of thrusting events by *Deramond et al.* [1993] in the central northern and southern Pyrenees.

[12] E-W trending folds and thrusts developed within the Mesozoic cover detached from its underlying basement above the Triassic evaporites [e.g., *Tempier*, 1987] (Figure 2b). The front of the allochthonous Provençal nappes connects westward to the front of the Languedoc nappes near Montpellier and farther west to the northern Pyrenean front (Figures 1 and 2). Shortening also caused inversion of preexisting Permian and Mesozoic extensional structures like in the Sainte-Victoire range in Provence (Figure 2b) or in the Pic Saint-Loup in Languedoc [*Roure and Colletta*, 1996]. In the southernmost onshore areas (Figure 2b) the Paleozoic basement is clearly involved in shortening, as in the Cap Sicié and the Nerthe structures where crystalline rocks were thrust onto Permian and Mesozoic formations during the Eocene [*Arthaud and Séguret*, 1981].

[13] *Tempier* [1987] estimated the amount of shortening accommodated by the Provençal fold-thrust belt at ~25–30 km. This value is deduced from balancing the deformation of the detached Mesozoic cover and the exposed Paleozoic basement of the hinterland (the Cap Sicié thrust displays a minimum shortening of 8 km) which lacks Mesozoic cover. Since crustal shortening in the offshore southern domain has not been taken into account, this estimate has to be considered as a minimum value. The same can be said about the 20–25 km of shortening determined in Languedoc on the basis of a restoration of a Late Jurassic limestone layer [*Arthaud and Laurent*, 1995] and not taking into account offshore basement shortening recognized on wells (e.g., Cicindelle well) and seismics. Although these estimates of shortening do not include most of the shortening in the Paleozoic basement of the hinterland, it is likely that the amount of shortening across the Languedoc-Provence segment remained lower than in the Pyrenees [*Olivet*, 1996].

[14] Folds and thrusts are geometrically and temporally linked to major NE trending strike-slip faults, such as the Cévennes, Nimes, or the Durance-Aix faults (Figure 2). These faults are inherited from the late Variscan tectonics [*Arthaud and Matte*, 1975] and were reactivated as transpressional left-lateral strike-slip faults during the Pyrenean shortening. These faults belong to a regional pattern of strike-slip faults extending from the eastern Pyrenees to NE Provence [*Mauffret and Gennesseaux*, 1989] (Figure 2) and are associated with basins and thrusts which developed in releasing-restraining bends and relay zones. The widespread transpressional reactivation of these inherited faults in Provence and Languedoc strongly suggests that shortening was associated with a significant wrench component in contrast to the western Pyrenees where shortening was presumably more frontal.

[15] Extensive analyses of kinematic or paleostress indicators such as fault slip data or calcite twin data have shown that the tectonic evolution of Provence was dominated by nearly N-S compression during the Late Cretaceous and Eocene [*Gaviglio and Gonzales*, 1987; *Lacombe et al.*, 1992]. Despite some stress perturbation near major fault zones [*Lacombe et al.*, 1992; *Arthaud and Laurent*, 1995] the Eocene stress field was remarkably stable in the north and south Pyrenean foreland and was characterized by nearly N-S horizontal stress trajectories. At the scale of the entire Pyrenean-Alpine foreland (European platform) the Eocene stress field was also dominated at that time by a nearly N-S compression [*Letouzey*, 1986; *Bergerat*, 1987; *Le Pichon et al.*, 1988]. This Pyrenean fold and fault pattern was partially truncated during the Oligocene E-W to NW-SE extension, which caused the transtensional reactivation of the Cévennes, Durance-Aix, and Nimes faults [*Séranne et al.*, 1995; *Mauffret and Gorini*, 1996; *Séranne*, 1999] and induced development of half grabens limited by shallow

**Figure 2.** (a) Detailed structural map of the Provence-Languedoc domain. The thick lines AA′ and BB′ refer to the cross sections. Thin dashed lines correspond to ECORS seismic lines. Thick dashed line corresponds to the offshore extension of the north Pyrenean Fault (NPF) (see text). ECM stands for external crystalline massifs. (b) Geological cross sections of the Provence-Languedoc domain. Light grey shading below the Provençal ranges represents Triassic evaporites, the pluses represent upper crust (basement), and the white/brick pattern represents Mesozoic-Cenozoic cover.

detachments beneath rollover structures [*Roure et al.*, 1992; *Benedicto*, 1996].

### 3.2. Late Cretaceous to Oligo-Miocene Tectonic Evolution of Corsica

[16] The main part of the island of Corsica is made of Paleozoic to Permo-Triassic granitoids which correlate with the continental basement of western Europe (Figures 3 and 4). The northeastern part of the island is occupied by the Schistes Lustrés nappe thrust above the continental basement of western Corsica [*Durand Delga*, 1984]. The contact between the Variscan and Alpine parts of the island is a southern extension of the Penninic front of the Alps [*Mattauer et al.*, 1981]. However, at variance with the Alps, shortening stopped in Corsica in the Oligocene and was taken over by extensional tectonics when the Liguro-Provençal basin started to rift [*Jolivet et al.*, 1990, 1991]. Alpine Corsica thus provides an image of the Alps frozen in the late Oligocene and reactivated by extension.

[17] The thrust front is well preserved where the unmetamorphosed Balagne nappe of Ligurian affinity rests above an Eocene foreland basin filled with olistostromes, conglomerate, and proximal flysch unconformably deposited on the Variscan basement [*Egal*, 1992]. Remnants of the Balagne nappe are found on top of the metamorphic domain farther east in the Nebbio syncline and along the east coast of Cap Corse near Maccinaggio [*Durand Delga*, 1984]. The extensional east Tenda shear zone reactivates the original thrust of the Ligurian nappe onto the Tenda granitoids and their Mesozoic cover near Saint Florent [*Daniel et al.*, 1996].

[18] Fragments of the European basement have been included in the accretionary complex during the subduction of the passive margin [*Mattauer et al.*, 1981]. The Tenda massif is made of Variscan and Permo-Triassic granitoids and a condensed Mesozoic cover (Figures 3 and 4). Two metamorphic episodes are recognized: first, a late Eocene stage in an HP/LT environment with limited pressures not higher than 9 kbar for a temperature around 400°C and, second, an Oligocene to early Miocene episode associated with the retrogression of HP/LT parageneses in the greenschist facies [*Lahondére and Lahondére*, 1988; *Fournier et al.*, 1991; *Caron*, 1994; *Jolivet et al.*, 1998].

[19] Radiometric ages for the peak of pressure in the Schistes Lustrés are variable from 80 Ma in the highest-pressure eclogites to ~45 Ma in the blueschists [*Lahondére and Guerrot*, 1997]. Younger ages around 35 Ma are probable in the Tenda massif where Eocene sediments show HP/LT metamorphic imprint [*Bézert and Caby*, 1988; *Brunet et al.*, 2000]. All other ages relate to the late exhumation during the formation of the Liguro-Provençal and northern Tyrrhenian basins between 25 and 33 Ma [*Brunet et al.*, 2000].

[20] The regional foliation is folded in two broad antiforms: the Tenda antiform in the west and the Cap Corse-Castagniccia antiform in the east (Figures 3 and 4). A klippe of the Balagne nappe and the Miocene Saint-Florent basin are preserved in the Nebbio synform in between [*Durand Delga*, 1984]. The main direction of stretching is E-W for both the high-pressure stage and the greenschist retrogression, but locally NS trending lineations can be found in the core of the Castagniccia antiform or along the western coast of Cap Corse in the eclogitic unit [*Mattauer et al.*, 1981; *Jolivet et al.*, 1990; *Caron*, 1994]. Synmetamorphic deformation shows two main stages: first, a top-to-the-west shear contemporaneous with HP/LT parageneses in all units and, second, a top-to-the-east shear localized along the main contacts, contemporaneous with the greenschist retrogression, more pervasive in the north [*Fournier et al.*, 1991].

[21] The contact between Ligurian units and the Tenda massif (east Tenda shear zone) shows a clear E-W lineation and top-to-the-east sense of shear associated with the retrogression of blueschist parageneses [*Waters*, 1990; *Daniel et al.*, 1996]. This deformation has yielded late Oligocene–early Miocene age and is related with the extensional episode that formed the Liguro-Provençal and Tyrrhenian basins [*Brunet et al.*, 2000].

[22] The contact between Alpine Corsica and western Corsica west of the Tenda massif consists of a fault zone which exhibits a complex evolution with evidence for left-lateral motion and normal displacement, the Ostriconi fault zone and its southern prolongation which has a clear morphological signature between the Balagne nappe and the Tenda massif [*Maluski et al.*, 1973; *Jourdan*, 1988]. At the scale of the whole of Corsica this fault zone branches onto a major NNW directed fault zone running between the western granitic basement and eastern Alpine Corsica, along which deformed narrow stripes of Mesozoic and Eocene formations display subvertical schistosity and vertical axis isoclinal folds; additional occurrence of horizontal striations on NW trending minor faults or schistosity planes supports a major wrench movement [*Maluski et al.*, 1973]. This fault zone was probably superimposed onto a preexisting late Hercynian strike-slip fault zone; this fault zone, especially the Ostriconi segment between the Tenda massif and the Balagne nappe, acted as a major ductile (semibrittle?) then brittle, left-lateral strike-slip fault during the Eocene [*Maluski et al.*, 1973], i.e., partly after the emplacement of nappes, and before the Oligo-Miocene extensional tectonics which reactivated it as a normal fault [*Jolivet et al.*, 1990]. When Corsica is backrotated into its initial prerift setting, this major strike-slip fault zone trends NE, that is, subparallel to the Cévennes, Nimes, and Durance-Aix faults.

[23] Alpine Corsica thus shows an evolution very similar to that of the internal zones of the Alps until the early Oligocene [*Jolivet et al.*, 1990]. This leads us to consider that the late Eocene tectonic history of northeastern Corsica was controlled by the southward subduction of Europe under Apulia, in contrast to the interpretations of *Treves* [1984] in which the eastern Corsica–northern Apennines system originated as an accretionary wedge produced by subduction of the Apulian microplate under the Corsica-Sardinia massif with contemporaneous development of units verging either toward the European or Adriatic margins. The tectonic evolution of Alpine Corsica was then disconnected from the main Alpine belt when back arc extension related to northward subduction of the remaining

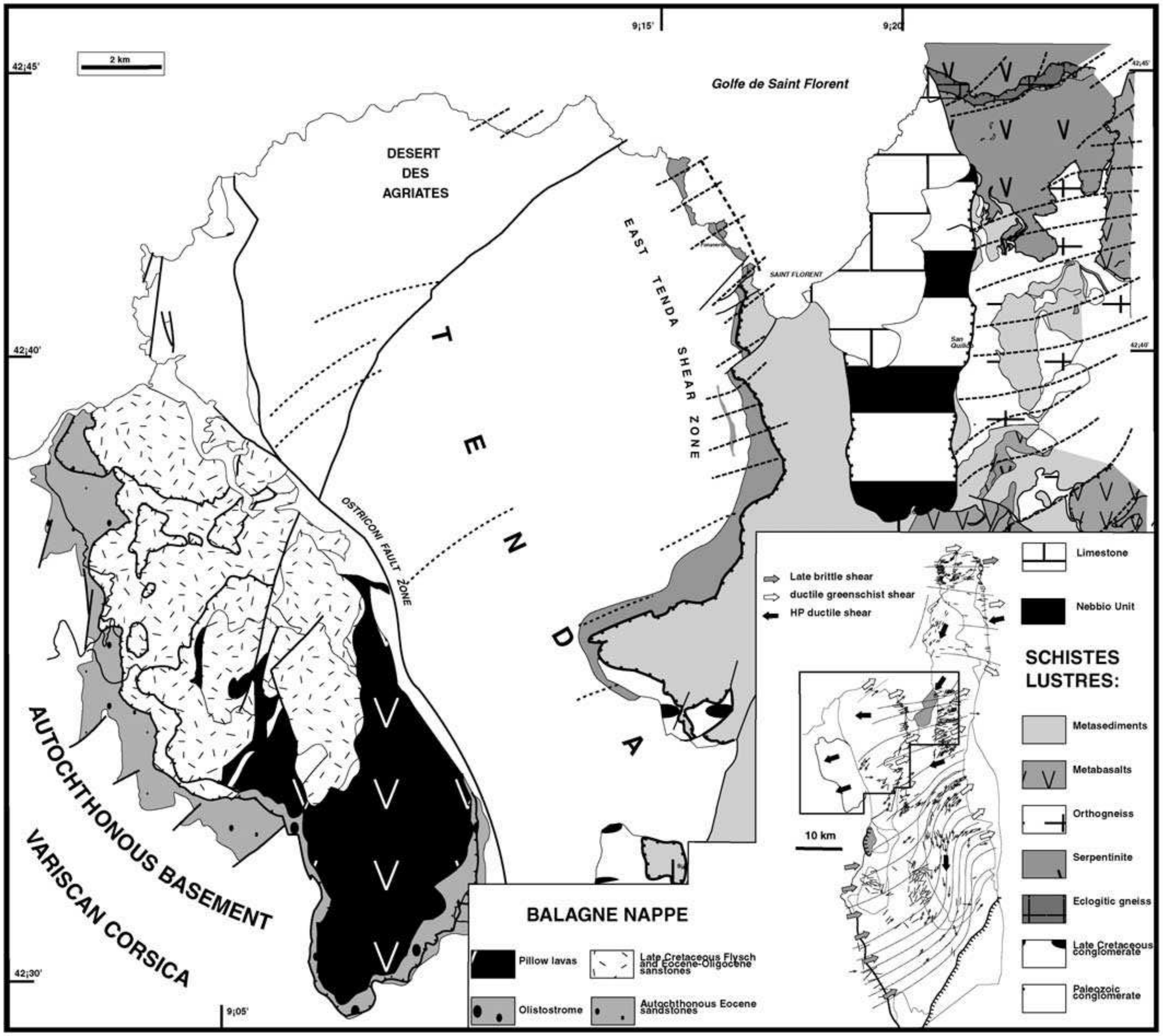

**Figure 3.** Tectonic map of the northwestern part of Alpine Corsica (Balagne nappe after *Jourdan* [1988] and *Egal* [1992]). Dotted lines represent the direction of stretching lineations. The insert shows the distribution of stretching lineations in Alpine Corsica [*Daniel et al.*, 1996; *Jolivet et al.*, 1998] and the location of Figure 4.

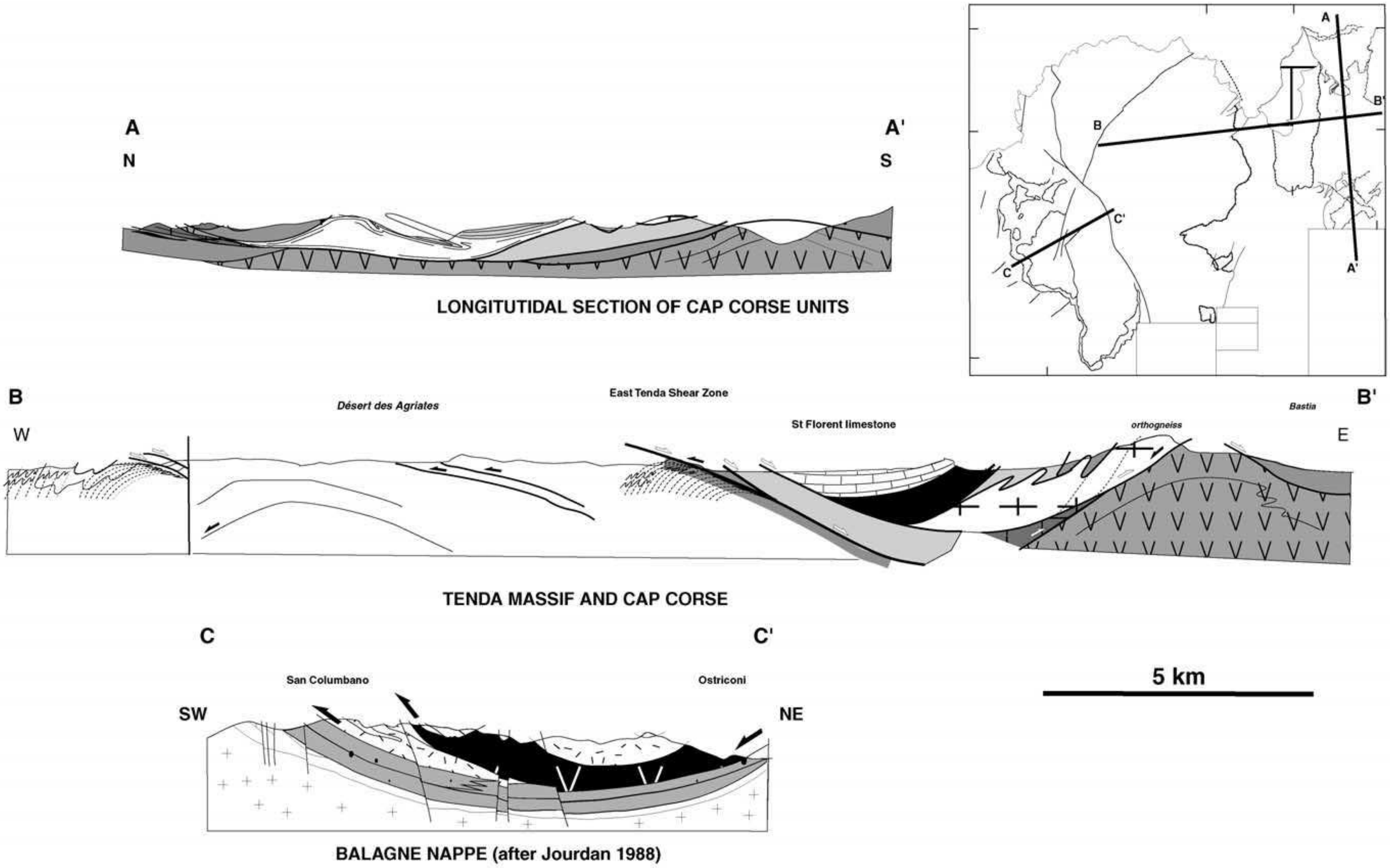

**Figure 4.** Same as Figure 3 but cross sections of Alpine Corsica.

part of Alpine Tethys under the Iberian plate started in the late Oligocene in response to the Africa-Eurasia convergence. All the ingredients of an oceanic subduction complex are present in the Schistes Lustrés nappe, and the internal parts of the paleocontinental margin are integrated in the accretionary complex until the early Oligocene. Part of the exhumation of HP/LT metamorphic rocks is accommodated by low-angle normal faults or shear zones such as the base of the Balagne-Nebbio nappe in the east or the east Tenda shear zone in the west, during the formation of the subduction-collision complex or afterward, during back arc extension [*Jolivet et al.*, 1990].

[24] East of Corsica, extension has produced the thinned crust of the northern Tyrrhenian Sea. East of the thick Oligocene to Quaternary Corsica Basin [*Mauffret et al.*, 1999], the Elba-Pianosa ridge shows evidence for top-to-the-east shallow-dipping extensional shear zones of late Miocene age [*Keller and Pialli*, 1990; *Daniel and Jolivet*, 1995]. Similar structures of late Miocene to Pliocene age are found further east in Giglio and in Tuscany [*Jolivet et al.*, 1998; *Rossetti et al.*, 1999, 2000]. These metamorphic core complexes and related intrusions were formed during the collapse of the internal parts of the Apennine-Alpine orogen [*Jolivet et al.*, 1998]. This domain shows unmetamorphosed Ligurian units resting on top of other Ligurian units and Tuscan units containing HP/LT parageneses. It is noticeable that along this transect the Apulian domain (Tuscan nappes) is structurally below Ligurian units as opposed to the Alps where Apulian units are at the top of the pile of nappes [*Decandia and Lazzarotto*, 1980].

## 4. Available Structural/Kinematic Models Do Not Account for Geological Observations in Provence-Corsica Domain

### 4.1. Building of the Pyrenees-Provence and Alps Overlap in Space and Time

[25] The Corsica-Sardinia block belongs to both the Pyrenean and Alpine domains, in agreement with all kinematic reconstructions which involve the initial fit of the Sardinia-Corsica block with the Languedoc-Provence domain. Although part of the deformation of Provence took place during Late Cretaceous–Paleocene times as deduced from the thick Late Cretaceous marine to lacustrine foredeep deposits or from evidence of early folding events associated with synkinematic breccia [e.g., *Tempier and Durand*, 1981], Pyrenean thrusting (and associated wrench movements along NE trending faults) in Provence and in the north Pyrenean foreland occurred until the late Eocene (Bartonian/Priabonian(?)), even until the Oligocene (section 3). Pyrenean shortening is therefore partially coeval with Alpine deformation in Corsica, since radiometric ages for the peak of pressure in the Corsican Schistes Lustrés extend from 80 Ma in the highest-pressure eclogites to ~45 Ma in the blueschists, with probable younger ages around 35 Ma in the Tenda massif where Eocene sediments show HP/LT metamorphic imprint. As a result, geochronological data do not support that Pyrenean shortening had totally ended when the Schistes Lustrés nappe collided with Corsica.

[26] Eocene times clearly represent a transition from a period dominated by the Iberia-Eurasia convergence (Pyrenees-Provence) to a period dominated by the Apulia-Eurasia convergence (Alps) and during which the major plate limit between Africa and Eurasia (northward dipping subduction) initiated. However, a discontinuous evolution involving completely independent Pyrenean and Alpine compressional histories before and after middle Eocene times as stated by recent reconstructions [e.g., *Stampfli*, 1993; *Stampfli et al.*, 1998] seems unlikely and unsupported by chronological data. There is a need of an alternative coherent and integrated structural scheme (Figure 5) and kinematic scenario (Figure 6) of the Provence-Corsica area during the Pyrenean orogeny, i.e., before and during late Eocene times.

### 4.2. Pre-Oligocene Crustal Shortening but No Oceanic Suture Between Provence and Corsica

[27] Since the present-day Provence-Languedoc coast cuts through the Pyrenean-Provençal structural pattern, well data and seismic investigations can be used to establish the southern extension of the belt. Recent papers have extensively described the structural pattern of the Provençal and Gulf of Lion margins [*Mauffret et al.*, 1995; *Mauffret and Gorini*, 1996; *Rollet et al.*, 2002] on the basis of a combination of well, seismic, magnetic, and gravimetric data. Accurate structural maps of the offshore domain are consequently available. The structural pattern is obviously dominated by the extensional features of the margin in relation to the thinning of the crust toward the SE, but it also shows preextensional compressional tectonics [*Mauffret and Gennesseaux*, 1989; *Mauffret and Gorini*, 1996] on which we will focus herein. Authors also consider an offshore eastward extension of the North Pyrenean Fault between Provence and Corsica [*Mauffret and Gorini*, 1996; *Séranne et al.*, 1995] (Figure 2), although available seismic reflection data are unable to locate it precisely. Two explanations are possible: Either this fault zone does not actually extend into this area, or else it consists of a rectilinear narrow subvertical shear zone lacking any significant vertical offset (transpressional or transtensional).

[28] In the Gulf of Lion, well data highlight the general reduction of Mesozoic formations. In certain instances, even synrift sediments are absent. This indicates that postcollisional stretching resulted mainly in the collapse of a high relief without preservation of synrift sediment [*Séranne et al.*, 1995]. Synrift and postrift Tertiary deposits of the Gulf of Lion directly overlay Paleozoic rocks, which are gently deformed, metamorphosed, and intruded by granites [*Cravatte et al.*, 1974]. These rocks are similar to those of the Pyrenean axial and northern crystalline zones and were also thrust northward in the Eocene over Permian and Mesozoic formations [*Mauffret and Gennesseaux*, 1989; *Arthaud and Laurent*, 1995]. Well data also give evidence for basement thrust onto sediments. This suggests that the region underwent crustal shortening, which probably led to significant crustal thickening.

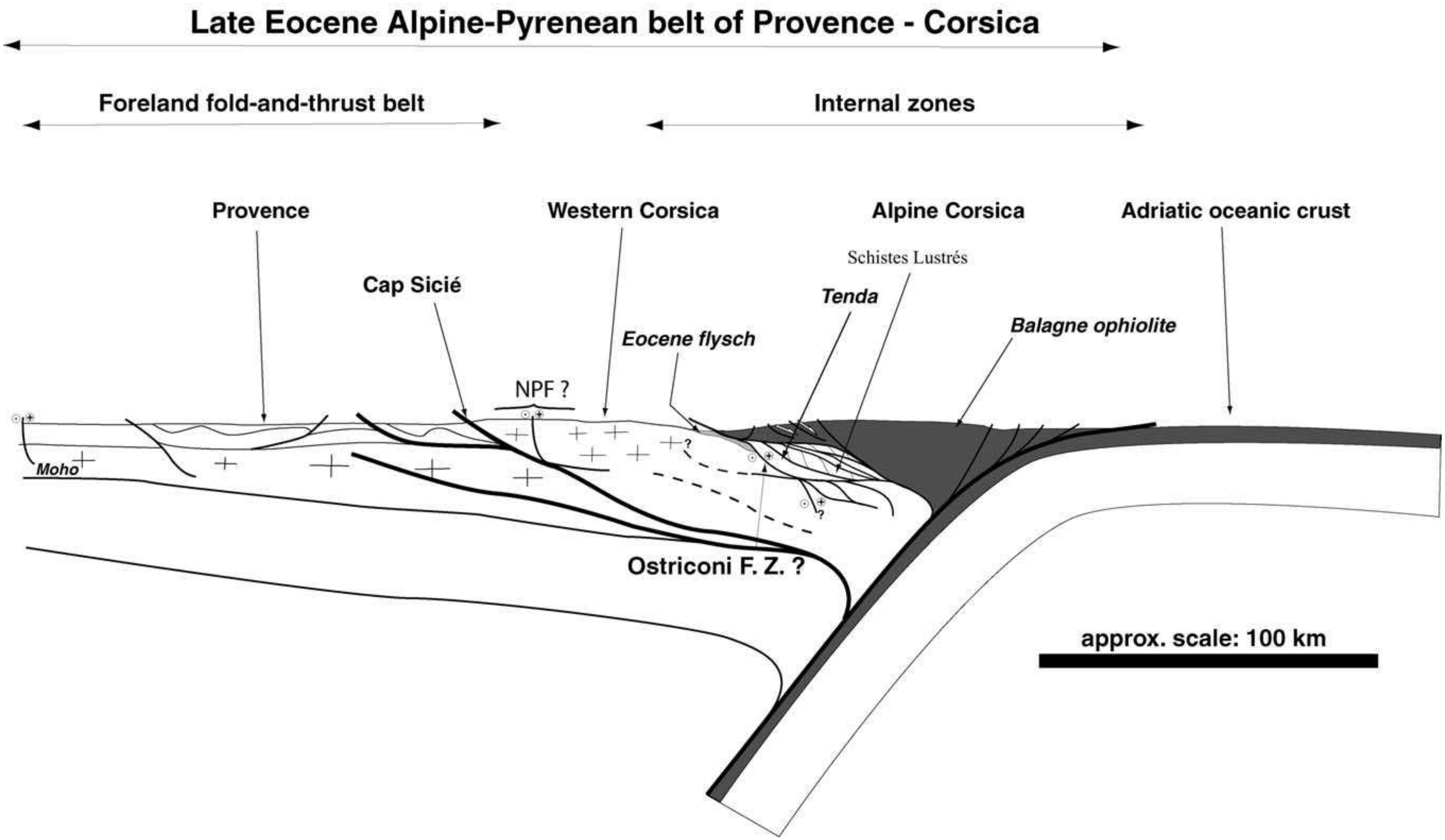

**Figure 5.** Tentative crustal-scale cross section of the Corsica-Provence belt in the late Eocene. F. Z. is fault zone.

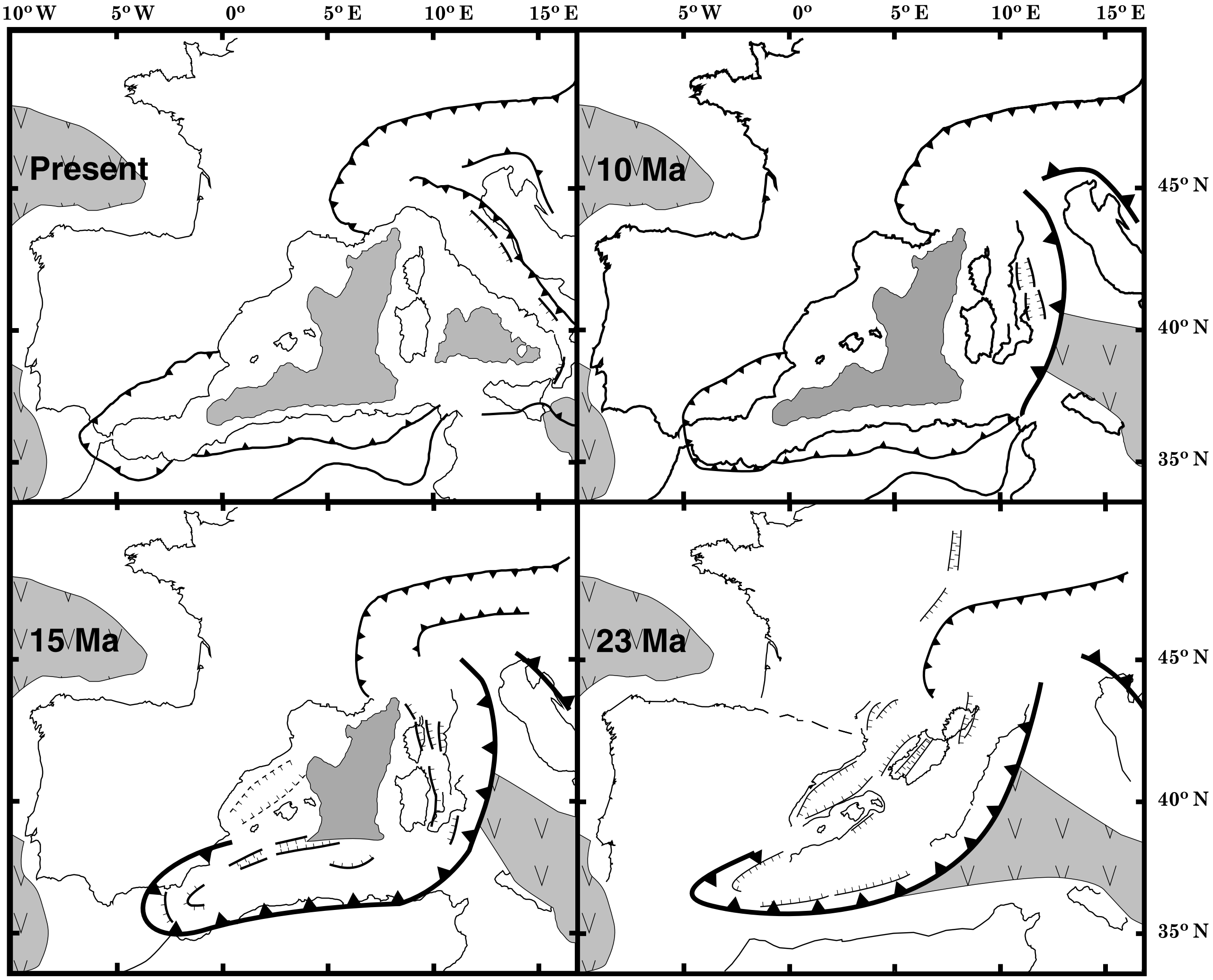

**Figure 6.** Kinematic reconstructions of the western Mediterranean since the Paleocene (see details in text).

[29] Seismic reflection profiles carried out in the deep part of the Gulf of Lion margin [*De Voogd et al.*, 1991] indicate significant crustal shortening prior to crustal thinning: Seismic lines show a number of S to SE dipping reflections in the basement (and few NW dipping ones [*Mauffret and Gorini*, 1996]), some of them extending with high amplitude down to the reflective lower crust and even into the upper mantle. These reflections are interpreted as major Pyrenean crustal thrusts by comparison with the onshore geology [*Bois*, 1993; *Séranne et al.*, 1995; *Mauffret and Gorini*, 1996; this study] (Figure 2b). Such thrusts may have reactivated former Mesozoic and/or Paleozoic faults and have been themselves sometimes reworked by Tertiary extension [*Mauffret and Gennesseaux*, 1989; *Mauffret and Gorini*, 1996]. Nearly similar SE dipping reflections observed in the Sardinia margin [*De Voogd et al.*, 1991] can also be tentatively interpreted as Pyrenean crustal thrusts.

[30] Offshore evidence of basement-involved shortening and emplacement of Alpine nappes has also been identified in the Ligurian domain (between Provence and Corsica) before its opening [*Rollet et al.*, 2002]. For example, at the foot of the Corsican margin, SE dipping reflections in the basement of the Glangeaud-Tenda seamount (the offshore prolongation of the Hercynian Corsican crystalline basement of the Tenda massif) have been interpreted as "Alpine" thrusts, which were probably reactivated as normal faults during Oligo-Miocene times [*Rollet et al.*, 2002]. These structures are similar to those found on the eastern flank of the Tenda massif and suggest crustal shortening prior to Oligo-Miocene extension, similar to the Eocene crustal shortening and thickening in the Gulf of Lion.

[31] Summarizing, prerift crustal thrusting related to the Pyrenean shortening occurred within the proximal and distal parts of the Gulf of Lion margins. Thrust faults are also suspected on the Sardinia margins, but evidence is too weak to draw definite conclusions. Together with the probable involvement of the basement in shortening in Provence (Nerthe-Cap Sicié), this suggests that the Pyrenean belt extended eastward at Eocene times.

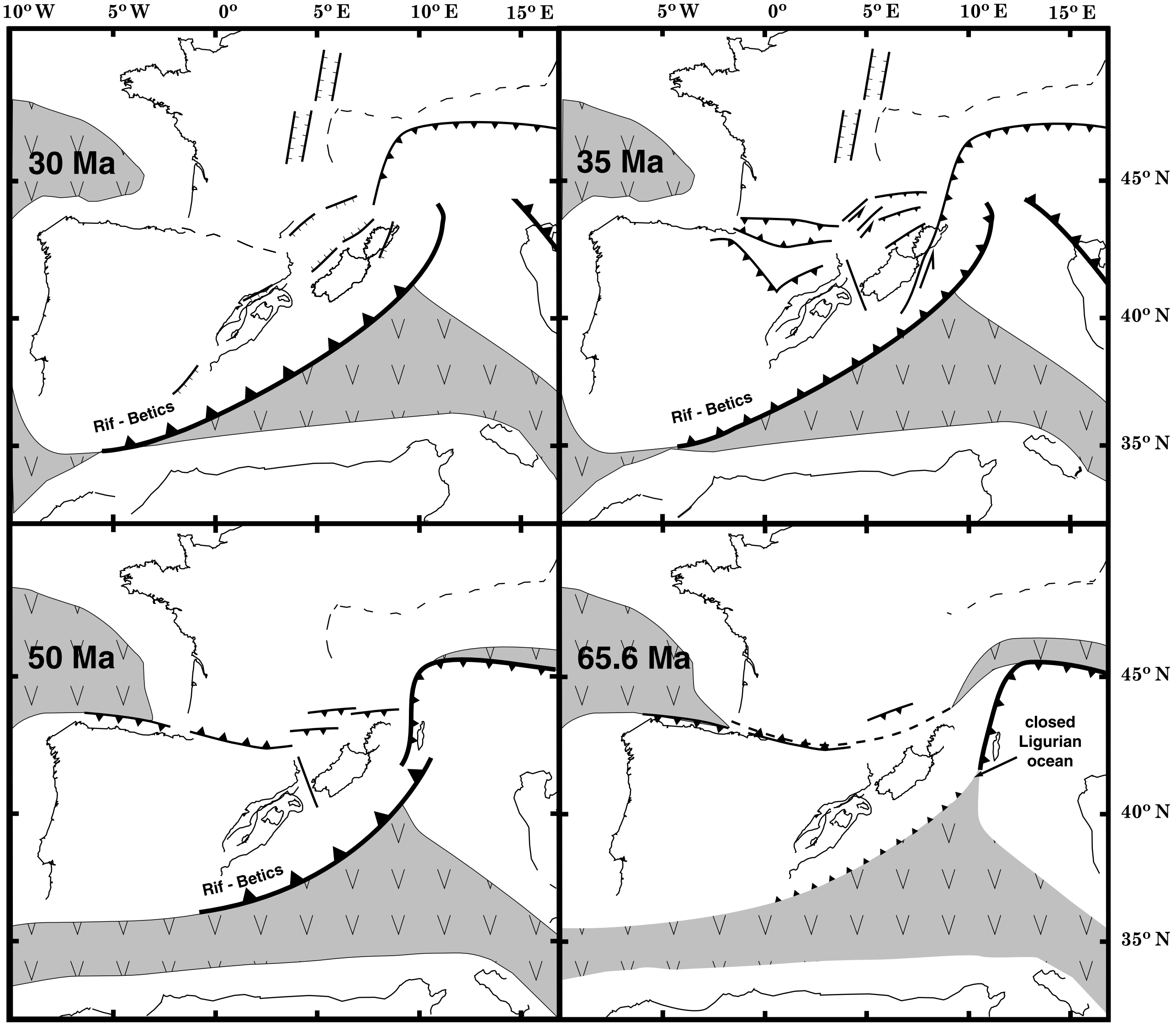

**Figure 6.** (continued)

[32] *Stampfli* [1993] and *Stampfli et al.* [1998] assume the existence of an oceanic domain in the Provence-Corsica domain (in fact, between Provence and Corsica) connecting the Valais ocean and the Pyrenean transtensional rift during the Cretaceous. This hypothetical oceanic domain started to close since the Cenomanian(?)-Turonian until the Senonian-Paleocene, before Corsica began to collide with Europe (the so-called Pyrenean phase). The intention of this model is to solve the problem of the important eastward shift of Iberia along the North Pyrenean Fault during the Cretaceous. In such a model the North Pyrenean Fault presumably extended eastward between Provence and Corsica, then into the Valais domain along the European margin; the connection to a paleotransform fault within the Ligurian-Piemontese domain allows a free eastward motion of the Iberian plate during the middle Cretaceous. This model differs significantly from the model by *Lemoine et al.* [2000] in which the domain connecting the Pyrenean rift and the Valais ocean has never been oceanized [*Lemoine et al.*, 2000, Figure 13.1, p. 142]. Stampfli's model meets the major difficulty that despite evidence for pre-Oligocene crustal shortening in the Gulf of Lion, there are no oceanic remnants, and therefore there is no geological argument in favor of the existence of a true oceanic domain in the future southwestern Alps-Provençal areas in the Cretaceous and of its subduction during the Late Cretaceous. Even assuming that the NPF extended between Provence and Corsica, for which there is lack of direct geological evidence, it can be argued that the component of Cretaceous transtensive motion in the area of interest was certainly low enough that there is no need to call for an oceanic domain and its closure along a southward subduction. The future Provençal domain underwent at best the inversion of the eastward extension of a Pyrenean-type rift during the Late Cretaceous–Paleocene

followed by crustal shortening, so there is no need to call for a major plate limit (oceanic suture) between Provence and Corsica. As a result, reconstructions by *Stampfli* [1993] and *Stampfli et al.* [1998] which consider that a single Paleogene subduction is responsible for the formation of the Pyrenean and Alpine belts, a subduction jumping from one ocean to the other through time, propagating into the Alpine Tethys during the Cretaceous and after the Paleocene to the northern margin of the Iberian plate (including Provence) where it gave birth to the Pyrenean-Provençal orogenic belt, are not supported by data.

### 4.3. Provence and Alpine Corsica Deformed Contemporaneously but in Different Ways in the Late Eocene

[33] Eastern Corsica shows a clear E-W shortening event which can be correlated with the evolution of the Alps farther north during the Late Cretaceous and the Eocene, until the early Oligocene, with development of HP/LT metamorphism (section 3). The pre- to post-Bartonian compressional deformation and top-to-the-west shear of the Tenda massif are contemporaneous with the Pyrenean compression in Provence. In western Corsica, tectonic evidence of Pyrenean N-S shortening are poor because outcrops are mainly made of late Hercynian magmatic rocks which display a complex pattern of fractures and are consequently not very suitable for unambiguously dating and therefore identifying the signature of the Pyrenean shortening. However, a clear Pyrenean tectonic imprint can be found in Sardinia, where outcropping formations which comprise Mesozoic to Cenozoic sedimentary rocks are much more suitable for identifying and dating Cenozoic deformation. An Eocene NW-SE shortening has been identified using striated microfaults, extensional veins, and stylolites [*Letouzey et al.*, 1982], mainly in the western part of the island. *Trémolières et al.* [1984] and then *Barca and Costamagna* [1997] provide additional structural evidence of middle Eocene folding and thrusting, leading to the recognition of a Pyrenean front along the present-day northwestern coast of Sardinia. These Sardinian structures can be considered as marking the eastern extension of the outermost part of the south Pyrenean zone.

[34] As a result, structural data firmly support that even though less deformed than its northern counterpart (Languedoc-Provence), the Corsica-Sardinia block was part of the Pyrenean domain at late Eocene times. At the same time, Alpine Corsica underwent an "Alpine-type" geological history dominated by emplacement of the Schistes Lustrés nappes under HP metamorphic conditions and was dominated by NW-SE shortening prior to rotation. The Corsica-Sardinia block therefore constitutes an "intermediate" domain that recorded both the Pyrenean and Alpine imprints. The problem of reconciling both late Eocene kinematics (N-S shortening to the west and NW-SE shortening to the east) has not been addressed by any kinematic reconstruction up to now; we propose that it involves partitioning of shear between the western and eastern parts, which may be partly accommodated by left-lateral strike-slip faults such as the Ostriconi fault zone between Alpine Corsica and western Corsica and whose kinematic importance could have been much greater than suspected in previous studies.

### 4.4. Engine Driving the Pyrenean Orogenesis Enigmatic Until Now

[35] Kinematic reconstructions [*Dercourt et al.*, 1986; *Le Pichon et al.*, 1988] suggest that at the end of Eocene times (~35 Ma) the main plate boundary between Africa and Eurasia was a north dipping subduction zone with its orientation changing from E-W south of Iberia to NNE-SSW east of Corsica and evolving eastward into the south Alpine–future Apenninic/central Mediterranean subduction zone. This subduction zone was probably already active as early as in the Paleocene-Eocene (50 Ma) along the southern margin of the Iberian plate. Indeed, most reconstructions of the area suggest that the slab below the Tyrrhenian Sea was once much wider and continuous from the Betics to the northern Apeninnes [*Abbate et al.*, 1986; *Dercourt et al.*, 1986; *Malinverno and Ryan*, 1986; *Dewey et al.*, 1989; *Doglioni et al.*, 1998]. The recent evolution during the southeastward slab retreat involved slab detachment beneath some parts of the Apennines and below the northern part of Africa [*Wortel and Spakman*, 1992, 2000]. Subduction-related volcanism [*Beccaluva et al.*, 1994] and back arc extension started some 30–35 Myr ago and suggest that by that time, 150–200 km of slab had already been subducted. All the models on subduction initiation suggest that convergence is very slow in the first stage [*Faccenna et al.*, 1999]. A likely minimum time to subduct the 200 km is thus 20–30 Ma. We can thus safely consider that the "Apeninne subduction" was already active some 50 Myr ago.

[36] During the late Eocene the Provence-Corsica domain was part of both the western Alpine domain and the eastern part of the Pyrenean domain. Therefore the Corsica-Provençal domain likely experienced the coeval effects of the ending collision of Iberia with Eurasia, the effects of the Apulia-Eurasia convergence leading to the emplacement of the Schistes Lustrés unit, and the effects of the north dipping subduction of Africa along the southern margin of the Iberian plate, which was probably the major plate boundary at that time. Available existing models do not take into account the simultaneous occurrence of underthrusting/subduction on the northern and southern margins of the Iberia-Corsica plate during the middle-late Eocene, with the northern (Pyrenean) zone of deformation becoming progressively inactive while the southern subduction of Africa beneath Eurasia-Iberia was becoming more and more efficient. In contrast to the Oligo-Miocene period when the length of the subducting African slab was important enough to induce rollback of the subduction hinge toward the SE and to cause back arc opening of the Liguro-Provençal basin, the regime of this southern subduction was rather compressional during the Eocene. The expected high level of mechanical coupling between the converging African and Eurasian-Iberian plates at that time presumably resulted in significant compressional effects within the upper plate, i.e., in Iberia and in the Provence-Corsica domain.

[37] More generally, before the major change in subduction dynamics from compressional to extensional in the

Oligocene [*Jolivet and Faccenna*, 2000] the late Eocene is characterized by a generalized compression from the Pyrenees, the Iberian Chain [*Casas Sainz and Faccenna*, 2001], the Betic Cordillera, and the Atlas [*Frizon de Lamotte et al.*, 2000], suggesting that Africa and Eurasia were mechanically coupled by the collision in the western Mediterranean. The engine of Pyrenean orogenesis, which has never been addressed because it was considered enigmatic until now, could be simply found in the transmission of compressional stresses evolving from the Africa-Eurasia subduction-collision zone; localization of Pyrenean deformation can be explained by inversion and further shortening of the Pyrenean rift domain and its eastward extension in Provence where the crust has been previously thinned during the Cretaceous.

## 5. A New Structural Model of the Pyrenean-Alpine Corsica Domain

### 5.1. Overall Geometry of the Provençal-Corsican Domain

[38] In terms of structural styles the allochthonous Provençal nappes constitute a typical foreland fold-thrust belt above a shallow décollement level (Triassic evaporites) cut by left-lateral strike-slip faults acting as lateral or oblique ramps. At the rear the pre-Permian basement is involved in shortening and behaved as a backstop for the detached cover [*Tempier*, 1987]. This domain of basement-involved shortening thus somewhat resembles the present-day inner part of the subalpine chains and the external Crystalline Massifs of the western Alps. It can also be considered as the eastern extension of the part of the Pyrenean belt located north of the North Pyrenean Fault which constitutes the boundary between the Iberian-Sardinian-Corsican and European plates and presumably extends offshore in the Gulf of Lion (Figure 2). Although no direct evidence has yet been found, the involvement of the basement in both the foreland (within-plate structural inversion) and inner portions of the belt presumably reflects the activation of a deep detachment within the continental crust [*Roure et al.*, 1996; *Vially and Trémolières*, 1996; *Lacombe and Mouthereau*, 2002]. The geological cross sections through the Provence domain shown in Figure 2b highlight the structural style governed by superimposed shallow and deep detachment tectonics, which probably accompanied crustal thickening in the inner part of the belt. At the rear is the Schistes Lustrés nappe associated with Ligurian ophiolites.

[39] In our view, Corsica and Provence can be considered parts of a single Alpine-Pyrenean belt, with an overall architecture very similar to that of the French-Italian Alpine belt but with rather dominating Pyrenean trends. It comprises a northern foreland fold-thrust belt (the frontal critical wedge made of Provençal nappes emplaced above a shallow décollement), a hinterland where crustal-scale thrusting occurs (crustal wedging above a deep-seated décollement), and an inner metamorphic belt made of obducted oceanic material which suffered HP metamorphism (Ophiolites/Schistes Lustrés).

[40] The reduced Mesozoic and Eocene sedimentary series wedged between the western basement massifs and the metamorphic belt represent the original sedimentary cover of eastern Corsica. The inner metamorphic belt was part of the crustal accretionary wedge along the Eurasia-Apulia subduction and was secondarily obducted during Eocene times onto the Eurasian margin, which was in turn shortened when western Corsica was involved in thrusting; both phenomena accommodated crustal shortening. This interpretation is in agreement with that of *Vially and Trémolières* [1996] but differs from that of *Carmignani et al.* [1995], in which the Corsica-Sardinia massif constituted the hinterland of the northern Apennines belt built during Oligocene-Aquitanian before the opening of the Ligurian basin.

[41] It is worth noting that the proposed geometry here is consistent with the geometry of structures east of Corsica, in Giglio and in Tuscany, where unmetamorphosed Ligurian units rest on top of other Ligurian units and Tuscan units containing HP/LT parageneses and therefore where the Apulian domain (Tuscan nappes) is structurally below Ligurian units, as opposed to the Alps, where Apulian units are at the top of the pile of nappes [*Decandia and Lazzarotto*, 1980]. Complete collision was thus never reached along this transect, and oceanic units make the uppermost unit on the Alpine and Apenninic side of the orogen.

### 5.2. Did the Pyrenean-Alpine Belt of Provence-Corsica Display a Typical Crustal Root?

[42] Crustal shortening presumably caused crustal thickening and crustal root development beneath the axial part of the belt, i.e., the present-day Provençal and Gulf of Lion margins, but there is no significant deformation recorded in western Corsica, and there are no available data in the Provençal margin to directly support this assumption. In any case, estimates of prerift crustal thickness need to be tested independently. Constraints on crustal thickness may be indirectly provided either by restoration of prerift crustal thickness based on fault patterns observed by seismics in the Gulf of Lion [*Benedicto et al.*, 1996] or by kinematic reconstructions of the initial fit between the Corsica-Sardinia block with the Languedoc-Provence area.

[43] Estimates of present-day mean crustal thickness and stretching of the continental shelf yield a value of 18–20 km and a stretching factor of ~1.16–1.22 [*Séranne*, 1999]; for the slope domain the stretching factor is ~1.32–1.51, and the estimated present-day crustal thickness is 12 km. These estimates lead to a prerift crustal thickness of ~25.5–27 km in the shelf area. The discrepancy between these estimates and the expected thickness of the crust related to Pyrenean thrusting in this area may be solved by considering either that thickening affected a preorogenic abnormally thin crust or that the thickened crust underwent a phase of synorogenic to postorogenic extensional collapse [*Gaulier et al.*, 1994] and/or basal attenuation during the late Eocene prior to Oligocene extension.

[44] The second type of constraints is given by kinematic reconstructions. The position of the Corsica-Sardinia block

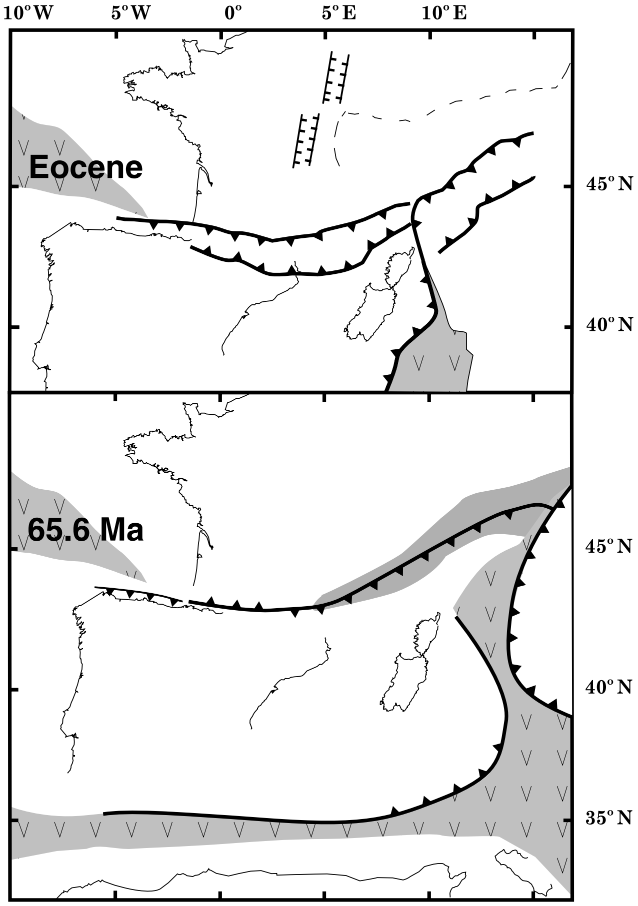

**Figure 7.** Kinematic reconstructions for 65.6 Ma and Eocene after *Stampfli* [1993] and *Stampfli et al.* [1998] placed in the same framework as reconstructions of Figures 6a-6b.

has been the subject of a number of kinematic reconstructions for Oligo-Miocene times, which basically rely either upon closure of the oceanic domain or upon the fit of the conjugate margins (see discussions by *Chamot-Rooke et al.* [1999] and *Gattacceca* [2001]). The description of all of these reconstructions is beyond the scope of this paper.

[45] The recent reconstruction of *Gattacceca* [2001] is based on the geometric fit of the conjugate margins and rotations deduced from paleomagnetism. It implies an amount of synrift motion of 60–70 km of southern Sardinia and 30 km of northern Corsica, the Corsica-Sardinia block behaving rigidly during rifting since the differential rotation of Corsica and Sardinia derived from paleomagnetic data occurred between 20.5 and 16–18 Ma [*Gattacceca*, 2001]. These displacements are therefore in agreement with the total extension of the Gulf of Lion estimated at 27–37 km [*Séranne*, 1999], assuming that the Sardinia margin underwent a nearly similar amount of stretching. However, this kind of reconstruction shares some limitations with reconstructions based on the extension of the oceanic basin, in particular gaps and overlaps. Assuming that the total crustal volume remained constant during extension, these misfits lead us to consider a laterally variable initial thickness of the prerift crust, as implied by numerical modeling by *Maillard and Chamot-Rooke* [2000]: An abnormally thin prerift crust is expected to lie in the Gulf of Lion (~27 km between Sardinia and Languedoc) and in the Gulf of Genoa (35 km between Provence and Corsica), with an abnormally thick prerift crust between.

[46] These estimates are therefore in relatively good agreement with the low prerift crustal thickness estimated from restoration of the stretched crust [*Séranne*, 1999]. However, they somewhat contradict the hypothesis of a “strong” crust (not affected by Mesozoic extension and Pyrenean orogeny) between Provence and Corsica [*Mauffret and Gorini*, 1996] on the basis of the steep and narrow character of continental slopes. They are also in poor agreement with the 45–50 km thick crust considered by *Vially and Trémolières* [1996] if no synorogenic to postorogenic thinning processes acted prior to Oligocene extension. Obtaining a prerift crustal thickness >30 km between Sardinia and Languedoc would require a displacement toward the NW of more than 70–80 km and of more than 30–40 km of Sardinia and of Corsica, respectively [*Olivet*, 1996].

[47] As a result, the problem of the crustal root cannot definitely be solved with the available structural, geophysical, and seismic data. Different scenarios, which are not mutually inconsistent, can be proposed to account for the apparent abnormally thin crust below the central part of the Pyrenean-Alpine belt of Provence-Corsica:

[48] 1. The crust was thickened during the Pyrenean orogeny and underwent a phase of drastic synorogenic to postorogenic extensional collapse and/or basal crustal attenuation during late Eocene prior to Oligocene extension; this is supported by the geometric relationships between dipping thrusts, the Moho (located by seismic refraction [*Hirn*, 1980; *Le Douaran et al.*, 1984; *Pascal et al.*, 1993]), and the lower crust, which suggest that metamorphism, magmatism, and/or delamination may have played a role in the removal of the likely crustal root [*Bois and Etude Continentale et Océanique par Reflexion et Refraction Sismique Scientific Parties*, 1991; *Bois*, 1993] in addition to the extensional collapse of the belt [*Gaulier et al.*, 1994] and Oligo-Miocene rifting. However, at the same time, there is no indication of some of the effects of root detachment, such as long-wavelength uplift or tomographic anomaly at depth or even widespread heat flow anomaly.

[49] 2. The Pyrenean thickening affected a preorogenic crust which has been significantly (and inhomogeneously) thinned by the Mesozoic extensional events [e.g., *Mascle et al.*, 1996].

[50] 3. The main part of crustal thickening has occurred either to the north, within the Mesozoic basin of SE France, which requires that it has suffered a significant amount of stretching during Oligo-Miocene times to account for the present-day absence of thick crust, or to the east, below and east of Corsica (below which a present-day 30 km thick continental crust is documented [*Bethoux et al.*, 1999]).

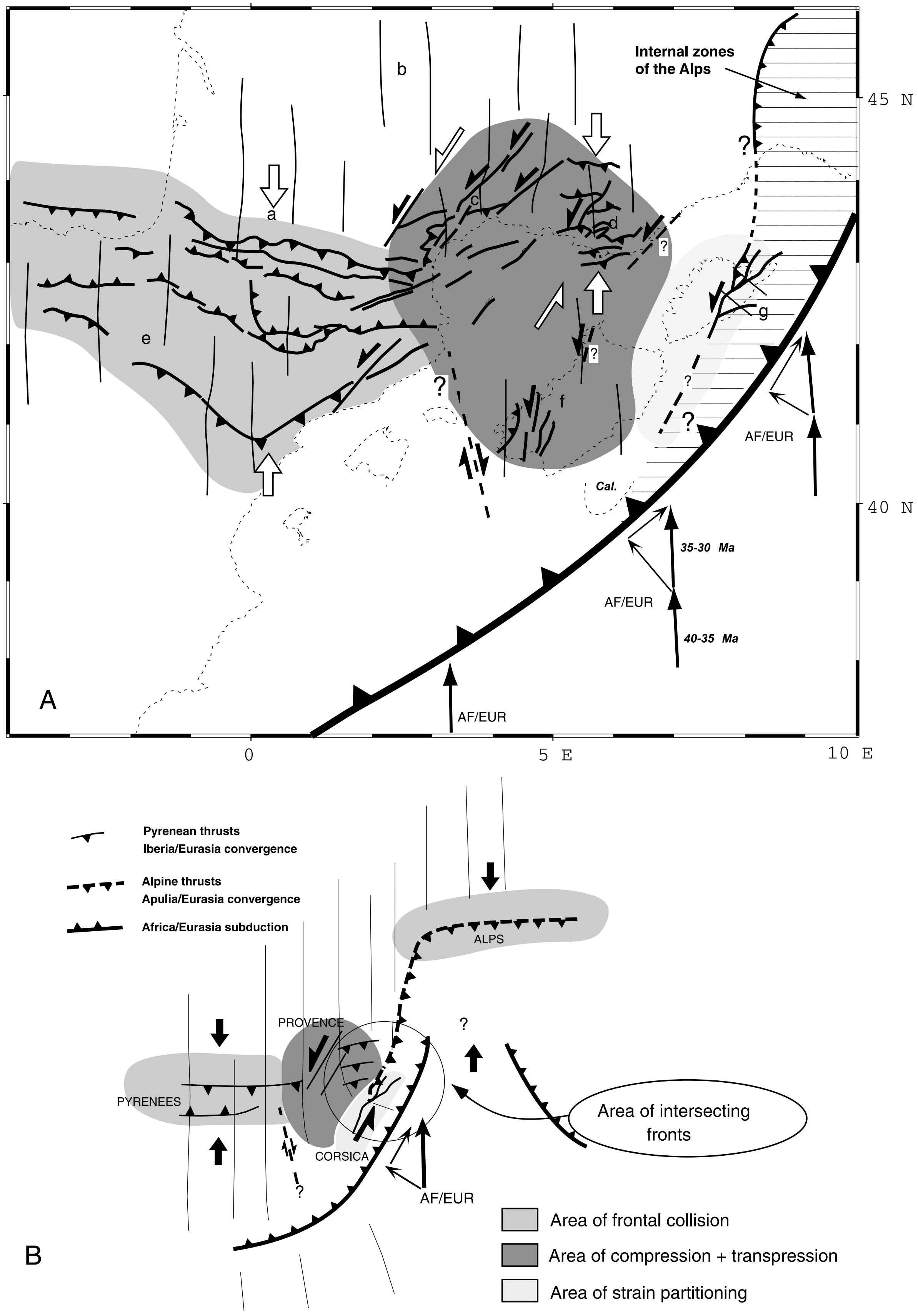
Internal zones of the Alps
45 N
40 N
0
5 E
10 E
a
b
c
d
e
f
g
?
Cal.
AF/EUR
35-30 Ma
40-35 Ma
A
Pyrenean thrusts
Iberia/Eurasia convergence
Alpine thrusts
Apulia/Eurasia convergence
Africa/Eurasia subduction
ALPS
PROVENCE
PYRENEES
CORSICA
Area of intersecting fronts
AF/EUR
B
Area of frontal collision
Area of compression + transpression
Area of strain partitioning

**Figure 8**

Therefore the crustal thickening was removed by Miocene extensional tectonics [e.g., *Jolivet et al.*, 1991, 1998].

## 6. A New Kinematic Model of the Pyrenees-Provence-Corsica-Alpine Domain Since the Late Cretaceous

### 6.1. Kinematic Reconstructions of the Western Mediterranean Since the Paleocene

[51] In this section we propose a new set of reconstructions based on the Africa-Iberia-Europe kinematics proposed by *Rosenbaum et al.* [2002a] and the paleoposition of Corsica and Sardinia after *Gattacceca* [2001] (Figure 6). Gattacceca's solution which is based on the most recent paleomagnetic analysis of volcanic rocks in Corsica and Sardinia leads to a slight override of Sardinia and the eastern part of Iberia in the latest Cretaceous–early Tertiary, which has been manually corrected. Our reconstructions are compared to Late Cretaceous and middle Eocene stages as proposed by Stampfli and coworkers (Figure 7). The hypotheses proposed by *Stampfli et al.* [1998] are placed in the same framework as our own reconstructions (Figure 6) to allow direct comparison.

[52] Figure 6 shows the paleopositions of continents and the main tectonic features active at the following periods considered:

[53] 1. At 65.6 Ma the Ligurian ocean has closed, giving the Schistes Lustrés nappe now found in the Alps and Alpine Corsica, while the Valais ocean is still to be subducted in the north. The southwestern extension of the Valais ocean toward the Pyrenean domain was accommodated through a series of transform faults inactive at this stage [*Lemoine et al.*, 2000]. Compressional deformation is recorded in southeastern France and along the Pyrenees. The front of the Alps is progressing westward. The future Apennine subduction is slowly forming south of Corsica-Sardinia, inducing compression to the north.

[54] 2. At 50 Ma the front of the Alps has moved westward, and the Valais ocean is about to be totally subducted in the north. Shortening is recorded along the Pyrenees and in Provence while the Iberian plate moves slightly northwestward, leading to the formation of a dextral fault between Sardinia and Iberia (as already mentioned by *Olivet* [1996]). The Appenines subduction is now fully running, and the first tectonic events leading to the formation of the Rif-Betic orogen are recorded (HP/LT metamorphism [*Monié et al.*, 1991]).

[55] 3. The period from 35 to 30 Ma is a key period at the scale of the Mediterranean region [*Jolivet and Faccenna*, 2000] because it marks the onset of the full collision between Africa and Eurasia and the inception of back arc extension in the whole region. The Apennine subduction is fully active, and arc volcanism is widely recorded. A maximum of compression is recorded from the Pyrenees and Provence to the Atlas chain [*Frizon de Lamotte et al.*, 2000]. Oblique convergence in the northern part of the Apennine subduction leads to shear partitioning across Corsica and Provence while the thrust front of the Alps has now reached Corsica, as discussed in more detail below (section 6.2). At 30 Ma the subduction regime has changed from compressional to extensional in the whole Mediterranean region, perhaps as a consequence of collision and slowing down of the northward motion of Africa [*Jolivet and Faccenna*, 2000]. Shortening is now recorded only in the Alps and along the Apennines accretionary complex while extension predominates in the back arc domain.

[56] 4. The period from 23 Ma to the present sees the amplification of back arc extension and the progressive retreat of the African slab eastward to reach the present position of the Apennines front and the present position of the Gibraltar arc [*Faccenna et al.*, 2004].

[57] Figure 7 shows the same area reconstructed with the hypotheses proposed by *Stampfli et al.* [1998]. The main differences lie in a rigid connection between the Briançonnais, Corsica-Sardinia, and Spain and in the presence of an oceanic gateway between the Valais ocean and the Pyrenean rift, thus between the Briançonnais and the Dauphinois in the French-Italian Alps, as well as in the paleoposition of Corsica and Sardinia with respect to Provence.

### 6.2. Kinematic Evolution of the Provence-Corsica Domain During Eocene Times

[58] The kinematic scenario proposed in Figure 8 focuses on late Eocene times. It interprets Eocene deformation in Provence and Corsica in the framework of the ending collision between Iberia-Eurasia and the active convergence between Apulia and Eurasia and between Africa and Eurasia, which led to the building of a Pyrenean-Alpine belt in the Provence-Corsica area (Figure 5).

[59] This kinematic scenario fits the following constraints: First, following left-lateral wrenching of the Iberian plate with respect to Europe, the late Senonian-Eocene convergence and collision of the Iberia-Corsica-Sardinia block with the southern margin of the European plate resulted in the Pyrenean orogeny, leading first to the closure

**Figure 8.** (a) Main tectonic regimes within the Pyreneo-Languedoc-Provençal-Corsican domain in the setting of the oblique Africa-Eurasia (AF/EUR) convergence (vectors at 35 Ma calculated after *Rosenbaum et al.* [2002a]). White arrows indicate the main deformation regime. Velocity triangles illustrate the trench parallel and trench normal components of motion. Thin lines indicate compression/shortening trajectories after *Rocher et al.* [2000] (region labeled a), *Tourneret and Laurent* [1990] and *Arthaud and Laurent* [1995] (regions labeled b and c, respectively), *Gaviglio and Gonzales* [1987] and *Lacombe et al.* [1992] (region labeled d), *Letouzey* [1986] and *Bergerat* [1987] (region labeled e), *Letouzey et al.* [1982] (region labeled f), and *Jolivet et al.* [1990] (region labeled g). Note the important role of the Ostriconi fault zone in partitioning strain. Cal stands for Calabria. (b) Schematic diagram showing the particular setting of the Pyrenean-Provençal belt at the intersection between Alpine and Pyrenean fronts in late Eocene times and model of accommodation of the obliquity of Africa-Eurasia convergence within the upper plate.

and the inversion of the Pyrenean-Provençal transtensional rift and second to crustal shortening and thickening until the Bartonian (Priabonian–early Oligocene(?)), giving birth to the Pyrenean-Provençal belt. The difference in amounts of shortening between the Pyrenees and Languedoc-Provence suggests occurrence of a paleotransform fault between the Pyrenees and Provence (and therefore between Iberia and the Corsican-Sardinian block) during collision [*Olivet*, 1996], as mentioned in section 6.1; the flip in asymmetry from the Pyrenees to Provence presumably coincides with the location of this paleotransform fault. Second, the present structural configuration of the Alpine sutures in the western Alps and in northeast Corsica suggests that prior to the Alpine continental collision at ~35 Ma these areas have been controlled by the same southeast dipping subduction system which was active during the late Eocene and leads to the emplacement of the HP Schistes Lustrés nappes.

[60] The initial shape of the major north dipping Africa-Eurasia subduction before the opening of the Liguro-Provençal basin and the Tyrrhenian Sea cannot be reconstructed without uncertainties, but in any case, a significant left-lateral obliquity of the convergence has to be taken into account. Considering the nearly N-S orientation of the convergence vector of Africa relative to stable Eurasia in the late Eocene (35 Ma) recalculated from recent reconstructions [*Rosenbaum et al.*, 2002a, 2002b], the along-strike change in trench orientation leads to a northeastward increase in obliquity of convergence from the Betics to the Alps, which superimposed onto the Iberia-Corsica-Sardinia collision and onto the coeval Alpine obduction in eastern Corsica. Taking into account its structural intermediate position, the deformation style and the kinematics of the Pyrenean-Alpine belt have probably been dominated by collisional strain partitioning and/or transpression. We propose that the kinematic setting of the locally oblique Africa-Eurasia convergence be correlated with the lateral changing type of deformation within the Pyrenees-Languedoc-Provence-Corsica domain. South of Iberia, the convergence was approximately normal to the trench, so the effects combined with the ending Iberia-Eurasia collision and nearly N-S contraction prevailed (Figure 8). The occurrence of regional transpressional deformation in Corbières-Languedoc marked by left-lateral motions along NE trending strike-slip faults (Cévennes and Nimes) reflects both the N-S directed Iberia-Eurasia shortening and the accommodation within the upper plate of the trench parallel component of motion related to the oblique Africa-Eurasia convergence. In the Corsica-Provence domain the trench strikes NNE, and therefore the obliquity is maximum; we propose that it has been partly accommodated in Corsica by partitioning between NW shortening to the east marked by NW trending lineations associated with the NW directed emplacement of Alpine Corsica ophiolitic and Schistes Lustrés nappes and by N-S shortening to the west (Figure 8). The two areas are decoupled by the Ostriconi left-lateral strike-slip fault zone that we interpret as a major crustal-scale feature. This partitioning probably did not accommodate the whole component of obliquity, and the remaining component of oblique convergence was accommodated by transpression accompanying thrusting in Provence-Languedoc.

## 7. Conclusion

[61] Corsica and Provence recorded a progressive shortening between 60 and 30 Ma owing to Africa-Eurasia convergence at the junction of two thrust belts, the Pyrenean and the Alpine thrust belts. The continental crust is shortened in the back arc domain of the future Apennine subduction with backthrusts verging toward Europe and western Corsica being overthrust onto the Provence foreland. Corsica, the future Apennines, and Provence together thus make a complete double-vergent mountain belt with internal zones in Alpine Corsica and northern foreland in Provence in the Eocene.

[62] For the first time our model proposes an engine for the Eocene shortening in Provence which so far has been quite enigmatic. Shortening is seen here as the consequence of stress transmission from the young subduction of Africa below the future Apennines. Compression then culminated in the west when the African and Eurasian plates collided in the late Eocene. During the Oligocene the subduction regime changed from compressional to extensional in the whole Mediterranean domain.

[63] Our model proposes an alternative view to previous plate reconstructions [e.g., *Stampfli*, 1993; *Stampfli et al.*, 1998] in that Eocene deformation in Provence and Corsica is interpreted within the framework of the ending collision between Iberia and Eurasia and coeval active Apulia/Eurasia and Africa/Eurasia convergence, which led to the building of a Pyrenean-Alpine belt in the Provence-Corsica domain. In this new model a major role is played by the dynamics of the Africa-Eurasia subduction zone and more precisely by the related regime of interplate coupling which controls both the stress transmission and the tectonic regime prevailing within the upper plate.

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