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Tectonics

RESEARCH ARTICLE

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Key Points:

- First lithospheric-scale balanced cross section of the Provence Chain
- Paleozoic structural control of subsequent episodes of deformation
- Orogenic crustal shortening of 155 km from the Late Cretaceous to Eocene

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Reconstruction of the Provence Chain evolution, southeastern France

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Abstract The Provence fold-and-thrust belt forms the eastern limit of the Pyrenean orogenic system in southeastern France. This belt developed during the Late Cretaceous-Eocene Pyrenean-Provence compression and was then deformed by Oligocene-Miocene Ligurian rifting events and Neogene to present-day Alpine compression. In this study, surface structural data, seismic profiles, and crustal-to-lithospheric-scale sequentially balanced cross sections contribute to the understanding of the dynamics of the Provence Chain and its long-term history of deformation. Balanced cross sections show that the thrust system is characterized by various structural styles, including deep-seated basement faults that affect the entire crust, tectonic inversions of Paleozoic-Mesozoic basins, shallower décollements within the sedimentary cover, accommodation zones, and salt tectonics. This study shows the prime control of the structural inheritance over a long period of time on the tectonic evolution of a geological system. This includes mechanical heterogeneities, such as Variscan shear zones, reactivated during Middle Cretaceous Pyrenean rifting between Eurasia and Sardinia. In domains where Mesozoic rifting is well marked, inherited basement normal faults and the thermally weak crust favored the formation of an inner thick-skinned thrust belt during Late Cretaceous-Eocene contraction. Here 155 km (~35%) of shortening was accommodated by inversion of north verging crustal faults, north directed subduction of the Sardinia mantle lithosphere, and ductile thickening of the Provence mantle lithosphere. During the Oligocene, these domains were still predisposed for the localized faulting of the Ligurian basin rifting and the seafloor spreading.

1. Introduction

The fold-and-thrust belt preserved in the Provence basin forms the eastern limit of the Pyrenean orogenic system in southeastern France, between the Alps to the northeast, and the Ligurian basin passive margin to the south (Figure 1) [Mattauer and Proust, 1967; Séguret, 1972]. The principal phase of shortening in the Provence segment occurred during the Campanian-Eocene period (named the Pyrenean-Provence compression), and this has been attributed to the collision between the Sardinia-Corsica continental block and Eurasia, and NW directed subduction of the Tethys (at least south of the Sardinia) (Figure 2) [Lacombe and Jolivet, 2005; Schettino and Turco, 2011; Schreiber et al., 2011; Molli and Malavieille, 2011; Advokaat et al., 2014]. This subduction system was connected eastward with the east directed Alpine subduction [Lacombe and Jolivet, 2005]. In contrast to the western Pyrenean segment, which underwent shortening until Miocene times as a result of the collision between Eurasia and Iberia [Desegaulx et al., 1990; Muñoz, 1992], the eastern Provence segment was affected by the opening of the north trending West European rift, and then by the NE trending back-arc rifting of the Ligurian basin and the seafloor spreading that was associated with the counterclockwise rotation of the Sardinia-Corsica block during the Oligocene-Miocene period [Hippolyte et al., 1993; Gattacceca et al., 2007]. This last major rifting event prevents any direct structural continuity between the Pyrenees and Provence belts. As a result, the inner structures of the Provence belt are now found in the Ligurian offshore basin and Sardinia-Corsica where some Pyrenean-Provence thrusts are suspected (Figure 2) [Lacombe and Jolivet, 2005]. The Eurasia-Adria collision and growth of the Alps were responsible for renewed Neogene to present-day shortening and deformation mainly in western Provence [Bergerat, 1987; Champion et al., 2000] and in localized salt basins in eastern Provence [Angelier and Aubouin, 1976]. The superimposition of these later tectonic phases strongly modified the overall geometry of the Provence Chain and makes it difficult to unravel its complete geological history.

The Provence Chain is a hybrid thick-skinned and thin-skinned belt [Bestani et al., 2015]. This structural setting was influenced by the preexisting basin architecture, which included reactivation of the Late Paleozoic crustal faults and heterogeneous Mesozoic sedimentary pile [Tempier, 1987; Roure and Colletta, 1996].

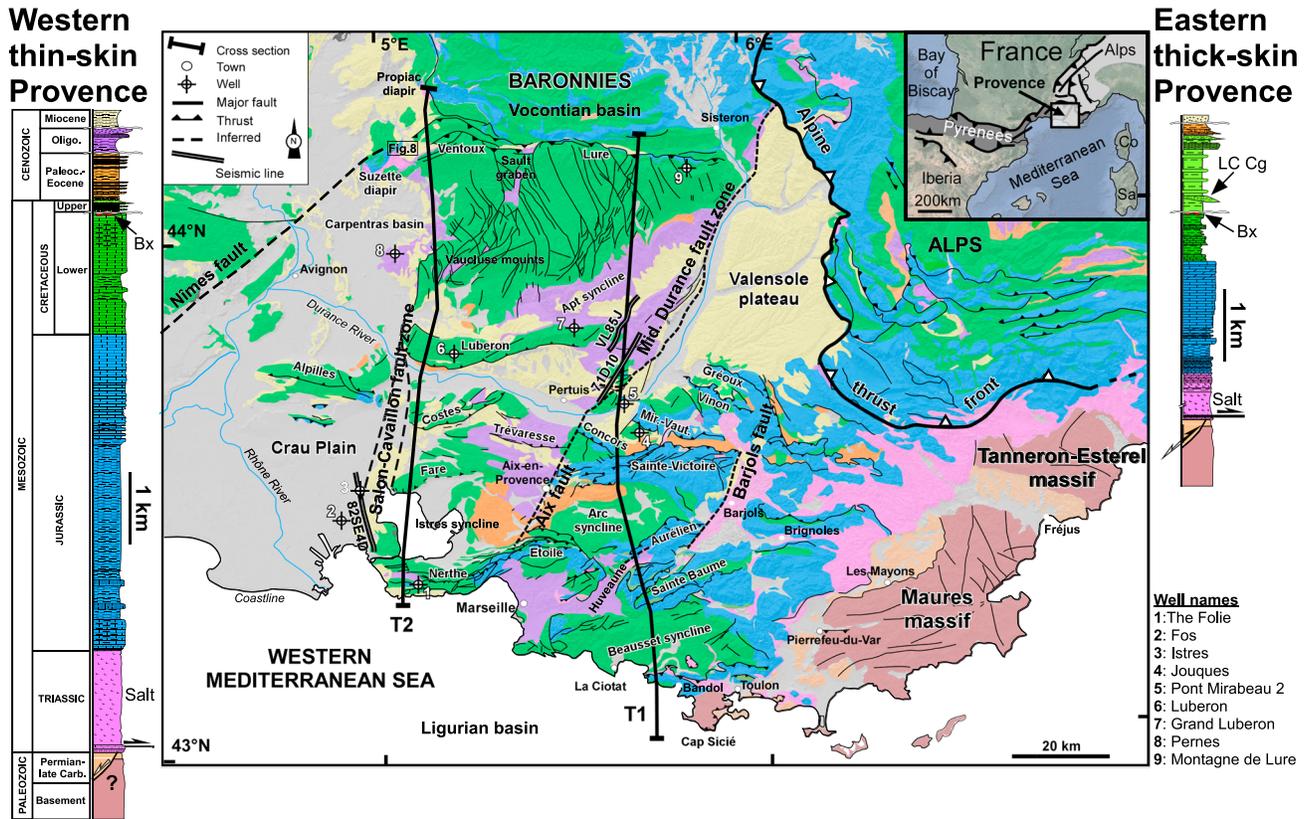


Figure 1. Geological and structural settings of the Provence basin (modified from Bestani et al. [2015]). Cross sections (T1 and T2) and wells are shown. Synthetic stratigraphic and lithotectonic sedimentary columns of the western thin-skinned Provence domain and eastern thick-skinned Provence domain are shown. Major unconformities are enhanced by a wavy line. Major décollement levels are shown. Co: Corsica. Sa: Sardinia. LC Cg: La Ciotat conglomerates. Bx: Bauxite.

Exhumation history of the sedimentary and basement units in Provence, Corsica, and Sardinia is well constrained by low-temperature thermochronometry data including zircon and apatite fission track and apatite (U–Th)/He data [Lucazeau and Mailhe, 1986; Morillon, 1997; Jakni, 2000; Zarki-Jakni et al., 2004; Fellin et al., 2005; Danišik et al., 2007; Bestani, 2015; Malusà et al., 2016]. Three groups of cooling ages can be distinguished: old ages ranging between 110 and 244 Ma, intermediate ages ranging between 35 and 80 Ma, and young ages ranging between 10 and 30 Ma. Old ages are found in Mesozoic cover and in Paleozoic basement of eastern Provence and Sardinia. These ages are interpreted as detrital ages in the cover units or as long-term erosion episodes in the basement units prior Late Cretaceous followed by small reburial below the Mesozoic-Cenozoic sedimentary cover [Danišik et al., 2007; Bestani, 2015; Malusà et al., 2016]. Intermediate ages are found in Paleozoic basement units of Provence, Corsica, and Sardinia. They are related to the Late Cretaceous-Eocene structural growth and erosion of the Pyrenean-Provence wedge also recorded by distributed growth-strata deposits in Provence and Sardinia [Espurt et al., 2012 and references therein; Bestani, 2015; Malusà et al., 2016]. Oligocene-Neogene cooling ages are found along the southeastern Provence coast and in Corsica and Sardinia. These young thermochronometric ages are related to a reheating and/or erosion episode during the back-arc rifting of the Ligurian basin associated with major volcanism [Jakni, 2000; Zarki-Jakni et al., 2004; Malusà et al., 2016].

Apart from regional structural geometry descriptions and some balancing and restoration tests [e.g., Tempier, 1987; Roure and Colletta, 1996; Lacombe and Jolivet, 2005; Terrier et al., 2008; Molliex et al., 2011; Espurt et al., 2012; Bestani et al., 2015], a comprehensive study of the structure, quantification of the shortening, and definition of the role of crustal-lithospheric inheritances in this outstanding segment of the Pyrenean orogenic system have not been achieved yet.

The aim of this paper is to reconstruct the crustal-scale to lithospheric-scale structural architecture, the kinematics, and the shortening of the Provence Chain, using surface, subsurface, and deep geophysical data,

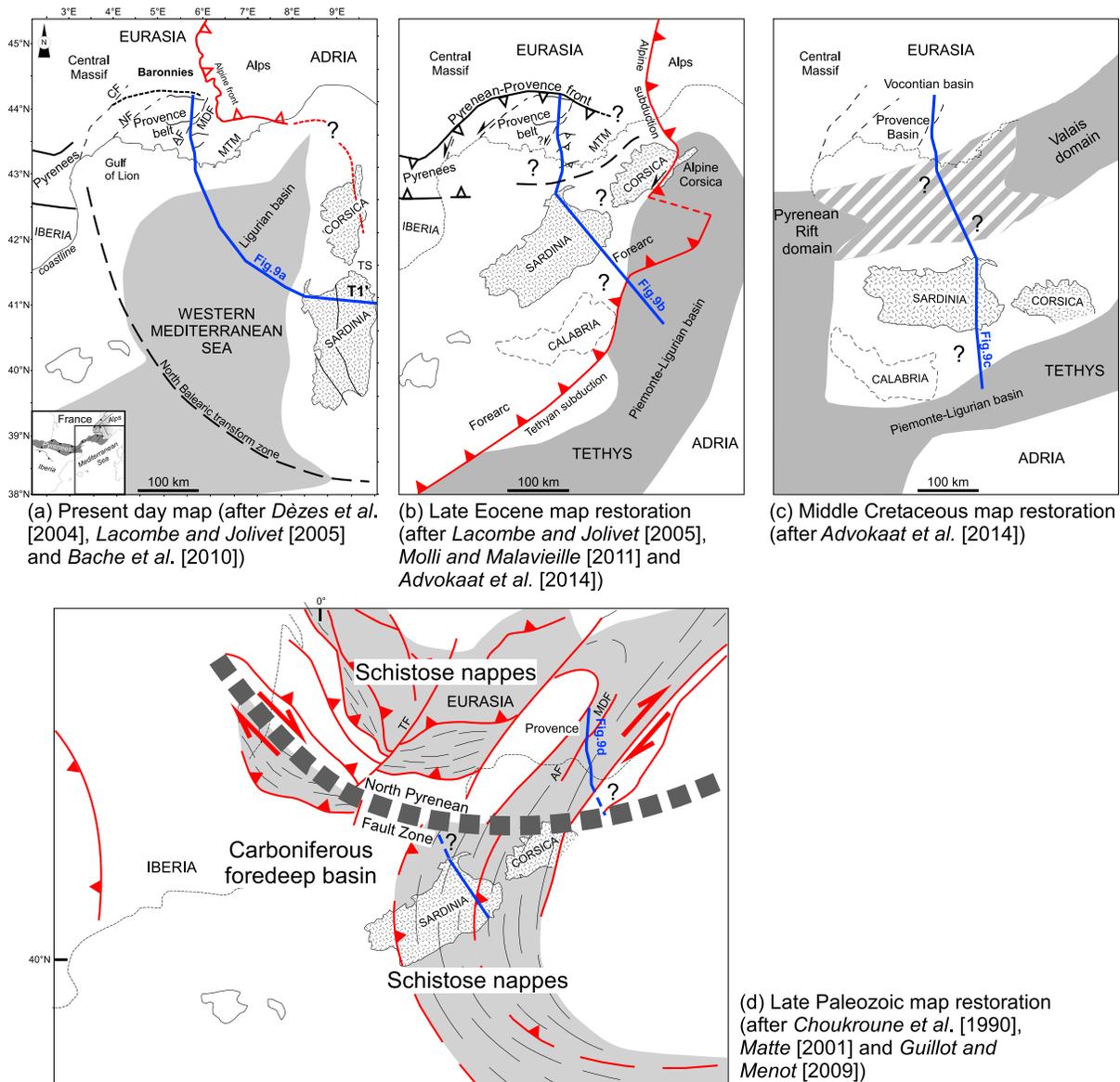


Figure 2. Tectonic map reconstructions of the Pyrenean-Provence orogenic system and western Mediterranean Sea from Paleozoic to present day (based on *Choukroune et al. [1990]*, *Matte [2001]*, *Dèzes et al. [2004]*, *Lacombe and Jolivet [2005]*, *Guillot and Menot [2009]*, *Bache et al. [2010]*, *Molli and Malavieille [2011]*, and *Advokaat et al. [2014]*). Location of cross-section T1' (Figure 9) is shown. CF: Cévennes fault. NF: Nîmes fault. AF: Aix-en-Provence fault. MDF: Middle Durance fault. TF: Toulouse fault. MTM: Maures Tanneron-Esterel massifs. TS: Tyrrhenian Sea.

and balanced cross sections together with paleogeographic reconstruction maps. This study has allowed us to evaluate the role of preexisting rift basin architecture on the evolution of this polyphase segment of the Pyrenean thrust belt, and it provides an insight into the Pyrenean and Mediterranean geodynamics along the Eurasian-Sardinian plate boundary.

2. Geological Setting

2.1. Regional Background

The Provence basin can be separated into two structural domains according to the NE trending Middle Durance and Aix-en-Provence faults, which is a major fault system that overlies a Paleozoic basement grain [*Arthaud and Matte, 1975; Guignard et al., 2005; Cushing et al., 2008; Terrier et al., 2008; Guyonnet-Benaize, 2011*] (Figure 1). These two domains can be defined as follows:

1. The southeastern domain corresponds to a complex tectonic domain made up of a thin (<4 km thick) Mesozoic to Cenozoic sedimentary cover and Variscan Maures and Tanneron-Esterel massifs to the south-east [Roure *et al.*, 1992; Masclé and Vially, 1999]. It is bounded by the Alps to the north-northeast (Figure 1). This domain is composed of an array of multidirectional structures that are oriented from N010°E to N120°E. The deformation of the cover was mainly defined by deep-seated basement thrusts that were associated with cover décollements and salt tectonics [Angelier and Aubouin, 1976; Tempier, 1987; Jannin, 2011; Espurt *et al.*, 2012; Bestani *et al.*, 2015]. From south to north, the southeastern thick-skinned belt consists of a series of structures: Cap Sicié (western edge of the Hercynian Maures massif), Beausset basin, Sainte-Baume, Aurélien Mount, Etoile, Nerthe, Arc basin, Sainte-Victoire Mountain, Concors, Mirabeau-Vautubières, Vinon, Gréoux, and Valensole Plateau (Figure 1). This domain shows structural and stratigraphic similarities with the Sardinia [Lacombe and Jolivet, 2005; Carosi *et al.*, 2005; Malusà *et al.*, 2016].
2. The northwestern domain corresponds to a trapezoidal panel made of a thicker (>7 km thick) Mesozoic-Cenozoic sedimentary cover that is bounded by the Baronnies basin to the north and the Nîmes fault to the west [Masclé and Vially, 1999] (Figure 1). The sedimentary cover is deformed by east trending spaced, long-wavelength thrust-related anticlines, and salt tectonic structures [Tempier, 1987; Rangin *et al.*, 2010]. From south to north, this domain comprises the following structures: Istres basin, Fare, Costes, Trévaresse, Luberon, Apt basin, Vaucluse Mounts, Carpentras basin, and Ventoux-Lure range (Figure 1).

2.2. Lithostratigraphy and Geodynamics of the Provence Basin and Sardinia

In the Provence basin, the oldest rocks are the Variscan granite and metamorphic series that are exposed in the southeastern Tanneron, Maures, and Cap Sicié massifs, close to the present-day coastline (Figure 1) [Onézime *et al.*, 1999; Rolland *et al.*, 2009]. These are unconformably overlain by ~1 km thick Late Carboniferous to Permian volcanoclastic and detrital series and lower Triassic detrital series that were deposited in NNE trending and ESE trending graben systems during the rifting phase of the Pangea [Delfaud *et al.*, 1989; Toutin-Morin *et al.*, 1993; Rolland *et al.*, 2009; Espurt *et al.*, 2012; Bestani *et al.*, 2015].

The Mesozoic–Cenozoic lithostratigraphy of units that are exposed in the Provence basin is illustrated in logs of Figure 1. Middle Triassic–Early Cretaceous rocks were deposited during the opening of the Tethys ocean, Pyrenean rift to the west, and Valais domain to the northern Alps [Handy *et al.*, 2010; Beltrando *et al.*, 2012; Bellahsen *et al.*, 2014]. Triassic rocks are dominated by basal detrital series and upper evaporitic series, with Keuper facies mostly made up of gypsum and clays [Arnaud *et al.*, 1990]. This upper mechanically weak level was locally involved in surficial salt tectonic structures, like Suzette or Propiac diapirs [Casagrande *et al.*, 1989] (Figure 1). The Jurassic and Early Cretaceous rocks consist of marine limestone in the eastern Provence, which evolves into thick basinal shale west of the Middle Durance fault system and toward the Vocontian basin, north of the Ventoux-Lure range (Figure 1) [de Graciansky and Lemoine, 1988; Léonide *et al.*, 2012]. North of the Ventoux-Lure range, and south of the Beausset syncline, locally the basin shows up to 1 km thick Late Aptian–Albian turbiditic and basinal series, which include olistoliths and breccias [Montenat *et al.*, 1986; Philip *et al.*, 1987; Montenat *et al.*, 2004]. These series were deposited in graben systems [Chorowicz and Mekarnia, 1992; Homberg *et al.*, 2013] during the Middle Cretaceous rifting, as the Pyrenean rift system [Debroas, 1990; Clerc *et al.*, 2012].

Bauxite development marked the long-lasting stratigraphic hiatus, from at least the end of the Early Cretaceous to the beginning of the Late Cretaceous, which was related to the “Durance uplift” between the Vocontian basin to the north and the Pyrenean rift system to the south [Masse and Philip, 1976; Chorowicz and Mekarnia, 1992; Guyonnet-Benaize *et al.*, 2010]. The bauxite is covered by Middle Cenomanian–Santonian transgressive marine sediments that range from a maximum of ~1.1 km in thickness in the Beausset syncline (Figure 1), which progressively overlapped northward [Philip, 1970]. Locally, the southern limb of the Beausset syncline comprises massive Turonian–Coniacian conglomerates (La Ciotat conglomerates) and Santonian sands (Figure 1). These terrigenous deposits record the erosion of a southward emerged basement high between Provence and the Sardinia [Hennuy, 2003].

Foreland deposition started in the uppermost Santonian in a marine environment and evolved into a general continental environment from the Campanian to Eocene, during northward propagation of the Pyrenean-Provence deformation front [Bestani *et al.*, 2015]. The Campanian–Paleocene series display massive alluvial fans with growth stratal geometries close to thrust-related anticlines, like the Etoile-Nerthe, Luberon, Sainte-Baume, or Sainte-Victoire structures [Corroy and Philip, 1964; Clauzon and Gouvernet, 1973; Leleu *et al.*, 2009; Espurt *et al.*, 2012] (Figure 1).

The Oligocene times were characterized by thick fluvial conglomerates, shale, evaporite, and lacustrine limestone [Hippolyte *et al.*, 1993] that were deposited in an extensional basin during the West European rift, which then saw the back-arc rifting of the Ligurian basin between Provence and Sardinia-Corsica block (Figure 2). The Miocene transgression was associated with a major planar erosional surface that was well developed in western Provence and was overlain by marine limestone and grainstone (Figure 1) [Besson, 2005; Oudet *et al.*, 2010; Demory *et al.*, 2011]. The Neogene compression was related to the growth of the Alps, and it is locally recorded by the Neogene continental growth strata [Clauzon *et al.*, 2011]. A drastic sea level fall related to the Messinian salinity crisis was responsible for the deep incised valleys in the present morphology of Provence [Clauzon *et al.*, 1996].

The Sardinia continental block is largely constituted by Variscan basement rock similar to the Maures massif [Carosi *et al.*, 2005; Rolland *et al.*, 2009; Rossi *et al.*, 2009]. The basement is overlain by thin Mesozoic platform sequences and Paleocene-Eocene syntectonic series that show similarities with Provence [Philip and Allemann, 1982; Busulini *et al.*, 1984; Marni *et al.*, 2007] and widespread Late Eocene to Quaternary volcano-clastic-series-filling grabens [Cherchi *et al.*, 2008].

2.3. Décollement Levels

Deep-seated basement faults inherited from the Late Carboniferous to Permian and the Early Triassic might have been preferentially reactivated during subsequent episodes of deformation [Lacombe and Mouthereau, 2002]. Upper Triassic series formed the main décollement level for thrusting during Pyrenean-Provence and Alpine compressions [Tempier, 1987]. Disharmonic shallower décollement levels are also found in the Middle Jurassic black shales and Berriasian limestones [Espurt *et al.*, 2012; Guyonnet-Benaize *et al.*, 2015].

3. Data Sets and Methodology

To constrain the structure of the Provence Chain, we used new field data, 1:50 000 Bureau de Recherches Géologiques et Minières geological maps and exploration wells. We also used depth-converted seismic reflection profiles provided by the Commissariat à l'Énergie Atomique et aux Énergies Alternatives [Guyonnet-Benaize *et al.*, 2015] (Figure 1). The depth geometry was constrained using published geophysical data for the Moho discontinuity depth, as determined by gravity data and *P* wave seismic tomography [Tesaro *et al.*, 2008; Garibaldi *et al.*, 2010], and for the crust-lithosphere thickness [Jiménez-Munt *et al.*, 2003].

A balanced cross-section technique is used to restore the basin geometry to the initial stages and to estimate the horizontal movement (shortening and extension). All of the above-mentioned data were integrated to balance and restore two cross sections across the external Provence fold-and-thrust belt (T1 and T2; ~120 km long) and a lithospheric-scale section (T1'; ~400 km long) that included the Ligurian basin, and the Sardinia and Tethyan subduction systems (Figures 1 and 2a). For the Provence belt, we used new structural data and the previously published Bestani *et al.* [2015] section. For the Ligurian basin, the Sardinia domain, and the Tethyan subduction system, we integrated data published by Guieu and Roussel [1990], Rollet *et al.* [2002], Dèzes *et al.* [2004], Lacombe and Jolivet [2005], Bache *et al.* [2010], and Malusà *et al.* [2016] (Figures 1 and 2). We also integrated tectonic reconstruction maps of Choukroune *et al.* [1990], Matte [2001], Guillot and Menot [2009], Molli and Malavieille [2011], and Advokaat *et al.* [2014] for location of the Sardinia during Late Paleozoic to present day.

Balancing and restoration were performed using the "Move" structural modeling software (Midland Valley Inc.) based on thrust tectonic concepts [Dahlstrom, 1969; Boyer and Elliott, 1982; Suppe, 1983; Suppe and Medwedeff, 1990; Shaw *et al.*, 2005], and bed-length and thickness conservation, and flexural slip algorithm for cover. Area-balance approach is used for the deep crust and mantle [Butler, 2013]. Cross sections were sequentially restored using regional stratigraphic data (see below). To calculate total extension and shortening amounts, cross-sections T1 and T2 are pinned in Baronnies in the north and near the Mediterranean coast to the south; lithospheric-scale cross section T1' is pinned in Baronnies in the north and on southern edge of the Sardinia crust.

The section orientation is orthogonal to the fold axes, in order to be parallel to the Late Cretaceous–Eocene N-S tectonic transport direction [Lacombe *et al.*, 1992]. The Provence basin is characterized by major NNE trending fault systems (Figure 1). These faults controlled deposition of the Mesozoic series and Oligocene-Miocene series and thrusting during Pyrenean and Alpine compressions [Lacombe and Jolivet, 2005]. Although the kinematic of these oblique faults is clearly established, the quantification of the oblique

movement is still not constrained. The Late Cretaceous-Eocene N-S shortening was mainly accommodated by regional NNE trending left-lateral strike-slip faults in the boundary between Languedoc and Provence (Cévennes and Nîmes faults) and in the eastern edge of Corsica (Figure 2b) [Lacombe and Jolivet, 2005]. We assume that the oblique motion along the NNE trending Middle Durance fault system is small at least west of the Valensole Plateau [Roure *et al.*, 2012] (Figure 1) and would not significantly affect the structural geometry but might affect the shortening estimates [Wallace, 2008].

Kinematic reconstruction of plate motion between Eurasia and Iberia-Corsica-Sardinia block indicates transcurrent motion at least during the Late Paleozoic [Matte, 2001; Guillot and Menot, 2009] and Late Jurassic, followed by orthogonal extensional stretching in the Middle-Late Cretaceous [Jammes *et al.*, 2009]. Late Paleozoic and Late Jurassic periods, which recorded major strike-slip motion, prevent precise reconstruction of the lithospheric-scale balanced cross section before Early Cretaceous.

4. Structure and Restoration of the Provence Thrust System

The following structural description of the Provence belt is separated into three parts from southeast to northwest, with regard to the geological map given in Figure 1 and the cross sections in Figures 3 and 4: (1) the southeastern Provence domain, where the deformation is mainly controlled by deep thick-skinned thrusting; (2) the central Aix-Middle Durance fault system; and (3) the northwestern Provence domain, where the deformation is mainly thin-skinned.

4.1. The Thick-Skinned Domain

On the basis of the structural and stratigraphic data, the previously published balanced cross section of Bestani *et al.* [2015] suggested that the structure of this domain is governed by deep-seated basement faults and salt structures (Figures 1 and 3). In the southern part of section T1 (Figure 3), the Late Paleozoic normal faults controlling pre-Triassic sedimentary basin geometry beneath the Bandol, Sainte-Baume, and Sainte-Victoire structures were deformed by gently south dipping basement thrusts propagating with short-cut trajectories (Figure 3). The Late Cretaceous-Eocene tectonic inversion of the inherited rift structures led to deep intercutaneous basement thrust wedges [Espurt *et al.*, 2012; Bestani *et al.*, 2015] and large thin-skinned thrust displacements through the complete transfer of the shortening from the basement faults to the cover décollements (i.e., the Bandol, Sainte-Baume, Aurélien Mount, and eastern Sainte-Victoire thrusts; Figures 1 and 3). Salt tectonic structures are found beneath the Bandol and Sainte-Baume thrusts [Bestani *et al.*, 2015].

In the southernmost part of section T2 (Figure 4), the Nerthe structure shows structural and sedimentary affinities with the eastern thick-skinned domain [Tempier, 1987]. This structure corresponds to an east trending anticline that is mainly constituted by Early to Middle Cretaceous series (Figures 1, 4b, and 5). Field data and cross-section construction suggest surficial southward thrusting in sedimentary cover on an $\sim 5^\circ$ N dipping ramp associated with small-scale north vergent thrusts [Dufaure *et al.*, 1969; Guieu, 1973]. The Nerthe anticline lies above a basement structural high that is associated with thin Mesozoic series compared to the Istres basin located to the north [Tempier, 1987; Andreani *et al.*, 2010]. We propose that the Nerthe anticline is separated from the Istres basin by a major east trending north dipping Mesozoic normal fault (Figures 4 and 6). This normal fault controlled thickness variations of the Mesozoic series. As previously speculated by Tempier [1987], we propose that the Nerthe high and its preexisting normal fault were decapitated by a later south dipping basement thrust located at ~ 9.5 km below sea level (bsl) during the Pyrenean-Provence compression (Figure 4). This thrust is assumed to have fed slip northward into the western Provence cover.

Salt tectonic structures related to Triassic series started to develop during the Jurassic to Late Cretaceous times and were then reactivated during the Pyrenean-Provence compression and Oligocene extension (e.g., Huveaune area; Figures 1 and 3) [Jannin, 2011; Bestani *et al.*, 2015]. Pyrenean-Provence thrust activity is mainly recorded from Campanian to Eocene (Figures 3b and 4b) by alluvial fan deposits that locally show spectacular growth strata patterns, as for the Sainte-Baume and Sainte-Victoire thrust-system areas [Leleu *et al.*, 2009; Espurt *et al.*, 2012; Bestani *et al.*, 2015]. The Pyrenean-Provence thick-skinned structures were cut by extensional fault systems and grabens during the Oligocene (Figures 5a and 5b), and then eroded (e.g., wave-cut platforms) and sealed by Aquitanian to Tortonian marine strata [Besson, 2005; Oudet *et al.*, 2010; Andreani *et al.*, 2010].

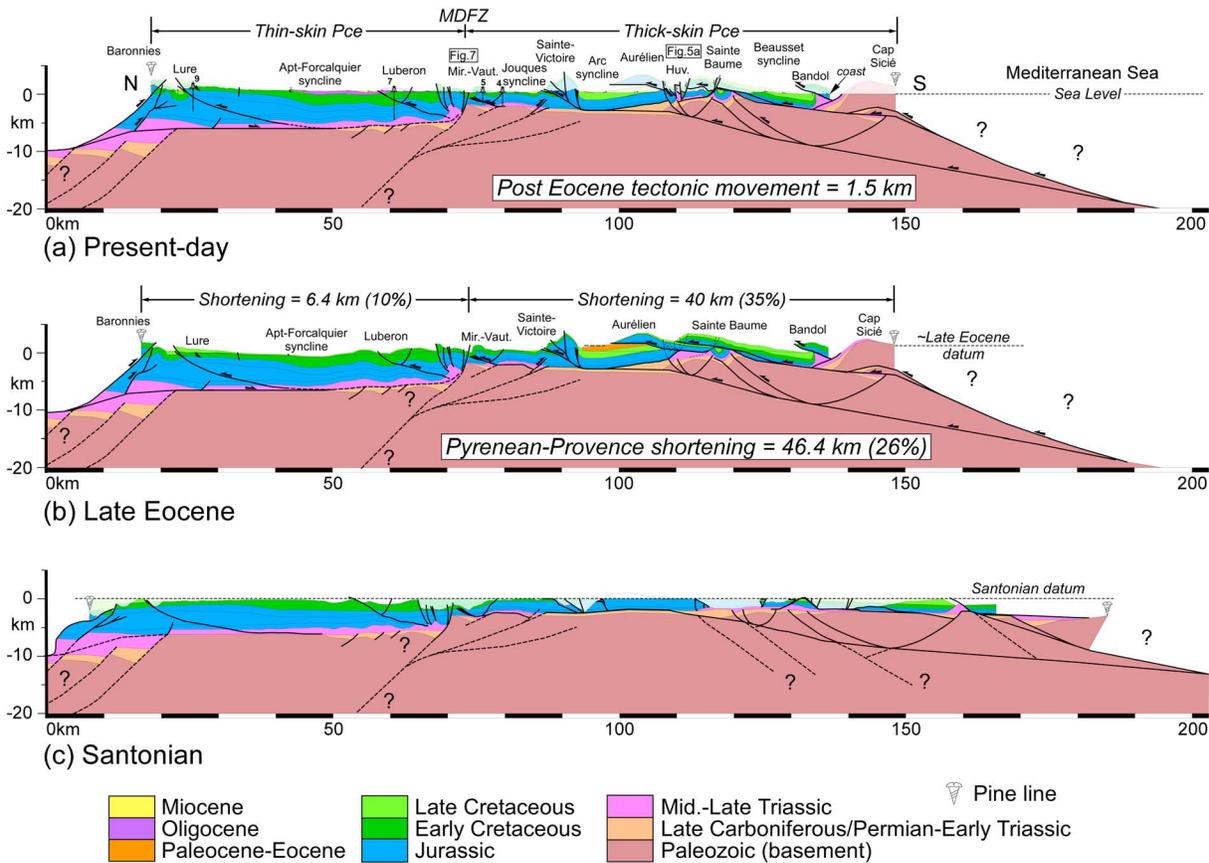


Figure 3. Balanced and restored cross-section T1. (a) Present day. (b) Late Eocene state at the end of the Pyrenean orogeny. (c) Santonian before the Pyrenean-Provence compression. For location, see Figure 1. MDFZ: Middle Durance fault zone.

4.2. Aix-Middle Durance Fault System

The Aix-Middle Durance fault system (Figure 1) has been studied on the basis of field, seismic-profile, and seismicity data [Cushing et al., 2008; Rangin et al., 2010; Guyonnet-Benaize, 2011]. Southward, this fault system connects with the Nerthe-Etoile thrust system, as a “horse-tail” system (Figure 1). This fault system is interpreted as overlying a NE trending Late Paleozoic basement grain like the Toulouse fault in the central Pyrenees [Arthaud and Matte, 1975; Burg et al., 1990] (Figure 2). It separates a thick sedimentary succession (>7 km thick) to the northwest, in contrast to the southeast (<4 km thick) [Ménard, 1980; Le Pichon et al., 2010; Guyonnet-Benaize et al., 2015], and forms the boundary between the thin-skinned and thick-skinned structural domains of Provence (Figures 1, 3, and 4).

Seismic profiles 71D10 and VL85J are located close to cross-section T1 (Figures 1 and 7), and these show that the Middle Durance fault zone is composed of a deep west dipping basement fault and a shallow listric normal fault that branches within Triassic evaporites [Roure et al., 1992; Benedicto et al., 1996; Roure and Colletta, 1996; Cushing et al., 2008; Guyonnet-Benaize et al., 2015]. The basement fault was mostly active as a normal fault during Mesozoic times [Roure et al., 1992], which allowed deposition of a thick sedimentary pile in the western Provence domain, whereas the sedimentary cover fault system was assumed to be reactivated during Oligocene and Miocene times [Guignard et al., 2005; Cushing et al., 2008]. The interpretation of seismic profile VL85J also suggests Late Paleozoic-Early Triassic extensional basins beneath the Middle Durance fault system (Figure 7). These inferred basement structures do not show structural inversion [Rangin et al., 2010; Guyonnet-Benaize et al., 2015]. The Middle Durance fault zone domain is seismically active, as revealed by present-day small seismic events ($M < 3.5$) distributed in the sedimentary cover and the historic seismicity [Cushing et al., 2008; Le Pichon et al., 2010]. These data suggest structural decoupling between the crustal part and the cover part of this fault zone [Cushing et al., 2008].

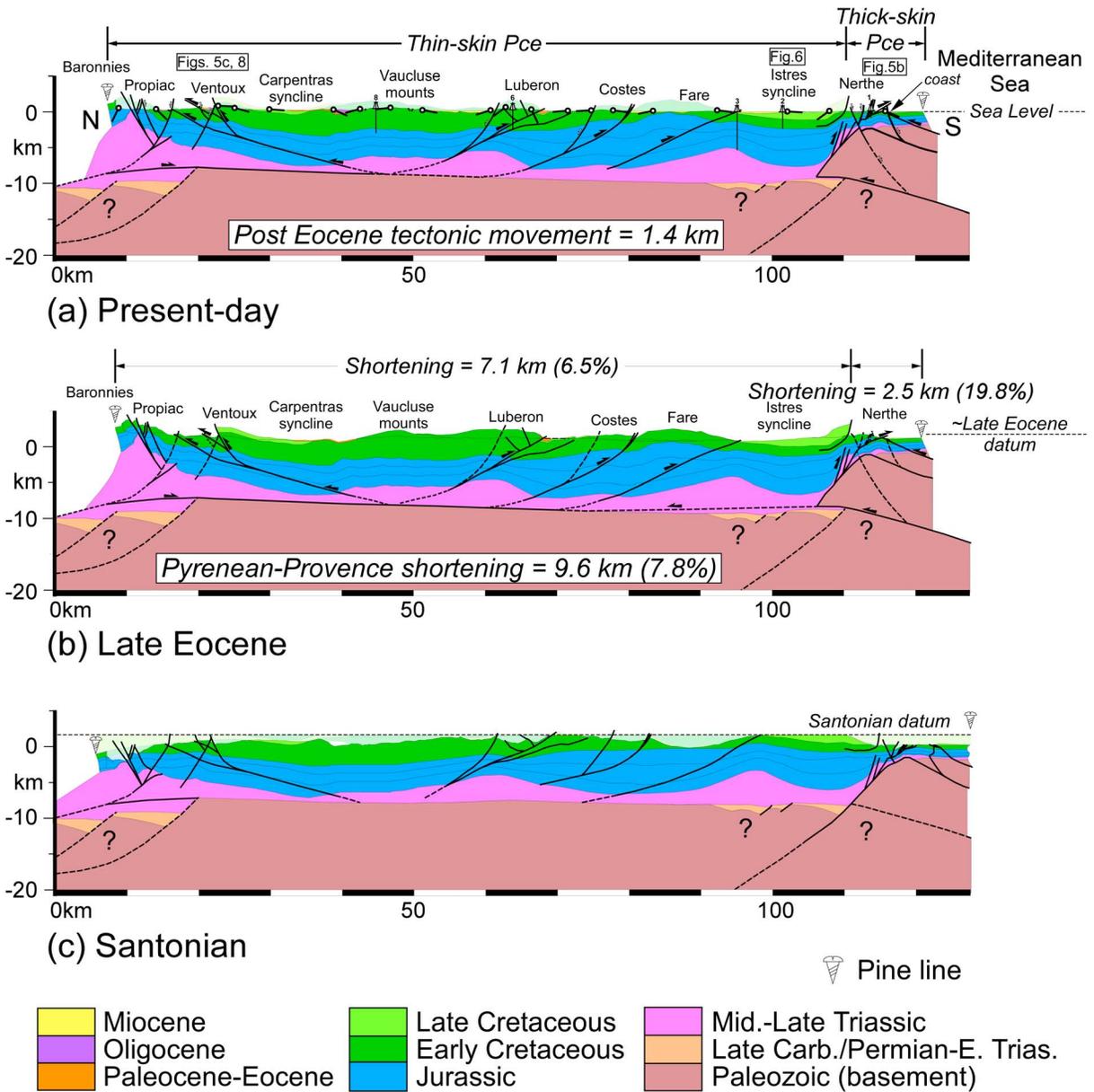


Figure 4. Balanced and restored cross-section T2. (a) Present day. (b) Late Eocene-Late Eocene state at the end of the Pyrenean orogeny. (c) Santonian before the Pyrenean-Provence compression. For location, see Figure 1.

4.3. The Thin-Skinned Domain

Northwest of the Aix-Middle Durance fault zone, the large-scale folding of the sedimentary cover is mainly controlled by the geometry of the underlying Triassic salt layer [Rangin *et al.*, 2010]. The construction of balanced cross sections together with sediment thickness data and subsurface data suggests that the basement-cover interface geometry of western Provence is poorly deformed [Tempier, 1987; Champion *et al.*, 2000; Terrier *et al.*, 2008; Rangin *et al.*, 2010; Mollieux *et al.*, 2011]. The basement-cover interface is located at ~6 km bsl along section T1 (Figure 3) and ~9 km bsl along section T2 (Figure 4), and at a depth of more than 10 km bsl under the southern edge of the Baronnies in the north.

The seismic profile 82SE4D in the southern part of section T2 (Figure 6) indicates that the Istres basin is a large syncline that is composed of thick Mesozoic series [Terrier *et al.*, 2008]. Its southern limb dips ~30° northward, while its northern limb dips 37° southward. The seismic profile highlights thickness variations in Middle to Late Jurassic series probably controlled at depth by a Triassic salt migration north of the

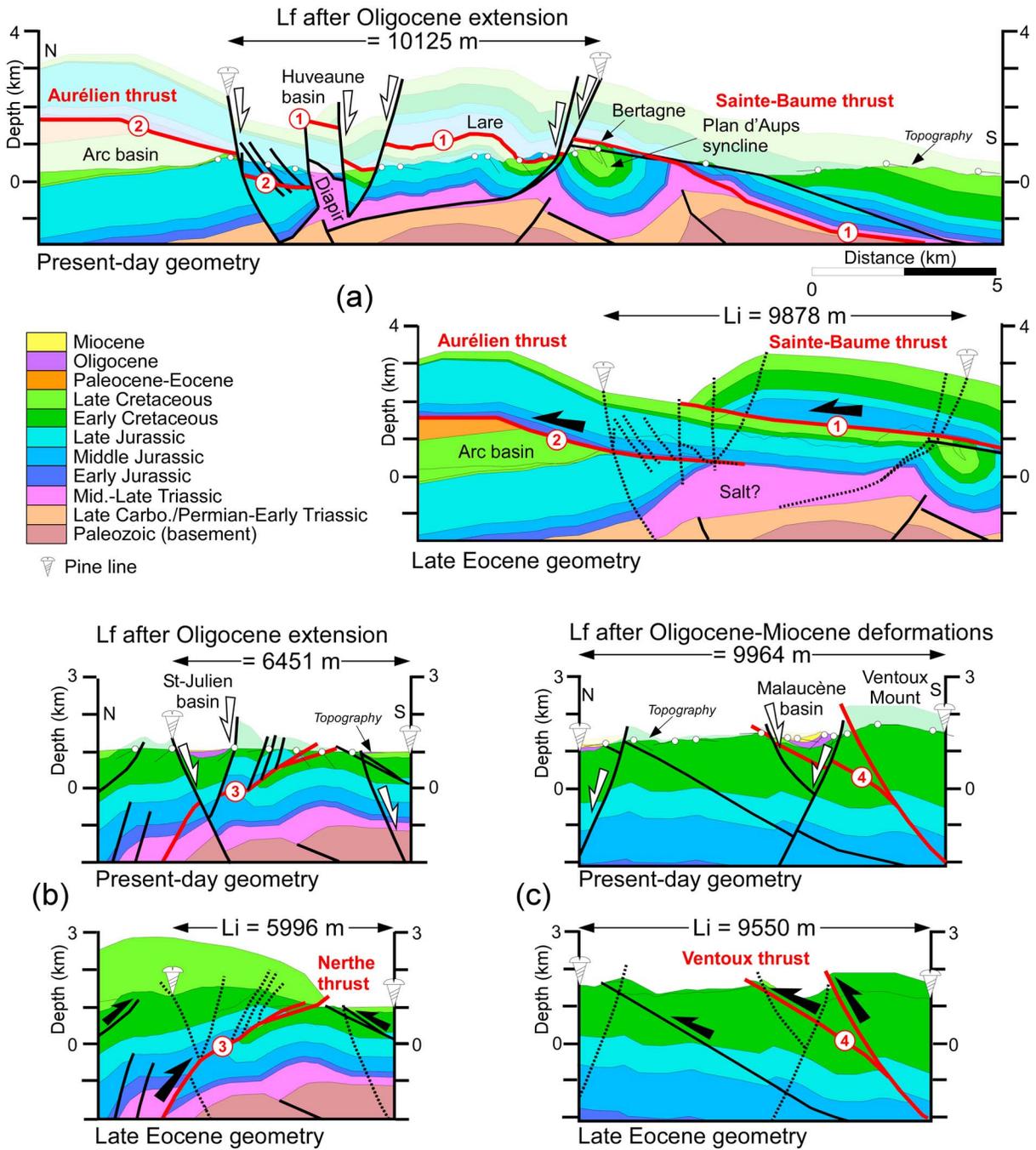


Figure 5. Examples of restoration of the Pyrenean-Provence thrusts (thick red lines). (a) The Sainte-Baume (1) and Aurélien (2) thrusts were deformed by a set of high-dipping normal faults, which included migration of Triassic salt (Huveaune basin). (b) Formation of the Oligocene St. Julien basin above the Nerthe thrust (3). (c) Formation of the Oligocene-Miocene Malaucène basin above the Ventoux thrust (4). For location, see Figures 3 and 4. L_i : Initial length. L_f : Final length.

Istres syncline. Northward, the sedimentary cover is deformed by two ENE trending and south verging thrust-related anticlines (i.e., Fare and Costes anticlines) (Figures 1 and 4). The initial activation age of these structures is probably ante-Eocene as revealed by the discordance of the Miocene strata on deformed Early Cretaceous limestones [Dubois, 1966]. A small post-Miocene reactivation of the Costes anticline is attested by deformed Serravalian-Tortonian strata on its southern flank (Figures 1 and 4) [Dubois, 1966; Champion et al., 2000].

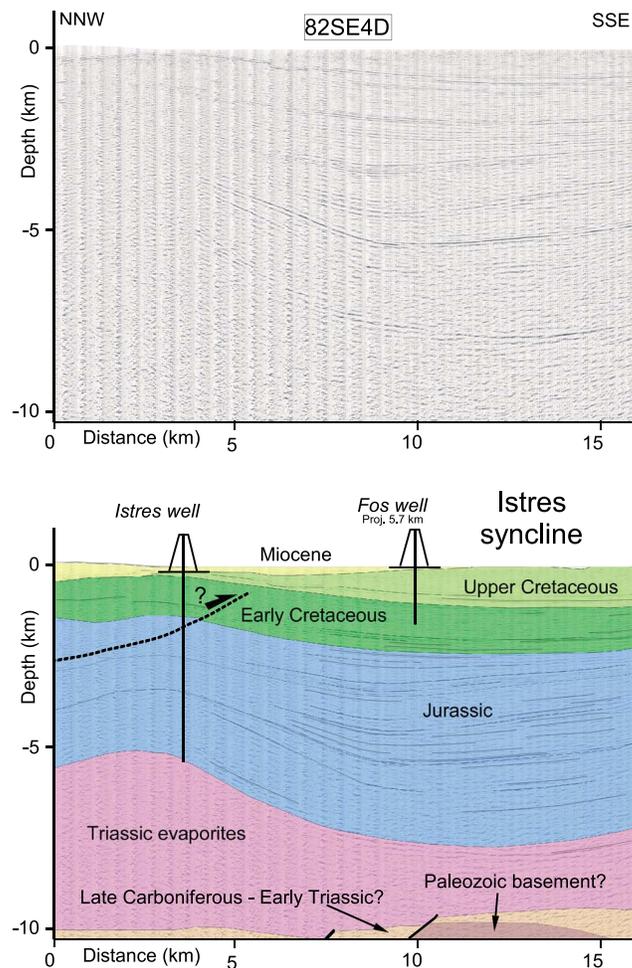


Figure 6. Interpretation of seismic profile 82SE4D across the Istres syncline close to section T2. For location, see Figures 1 and 4a (cross-section T2).

The Luberon anticline forms a major curve-shaped range of about 65 km long that is bounded by the Middle Durance fault zone to the east and the Salon-Cavaillon fault zone to the west (Figure 1). Along cross-section T2, the western Luberon thrust is a broad south verging breakthrough fault-propagation fold formed of thick lower Cretaceous limestone (Figure 4). This anticline shows a 10°N dipping backlimb and a 70°S dipping forelimb. The forelimb shows locally massive (~300 m thick) Paleocene-Eocene breccia deposits with growth strata geometry that records the initial growth of the Luberon anticline during the Pyrenean-Provence compression [Clauzon and Gouvernet, 1973; Villegier and Andrieux, 1987]. The western Luberon anticline is globally covered by Burdigalian-Serravallian strata and Miocene wave-cut platforms [Besson, 2005]. Along section T1, the eastern Luberon structure is a north verging thrust-related anticline associated with a south verging back thrust (Figure 3). The recent compressional reactivation of eastern Luberon was recorded as before the Messinian salinity crisis [Clauzon et al., 2011]. The 71D10 and VL85J seismic profiles reveal that the eastern Luberon ramp

dips ~15° through the Middle Jurassic to Cenozoic series (Figure 7). The thrust probably connects down in the Triassic evaporites along the Middle Durance fault zone.

The Apt basin is a 20 km long and 40 km wide slightly deformed syncline that is filled by ~600 m thick Oligocene to Tortonian series (Figures 1 and 3). This basin was transported northward on the Ventoux-Lure thrust system, which is an east trending 65 km long range (Figure 1). The Ventoux-Lure range superimposes on a major Early Cretaceous paleogeographic limit that delimited the Vocontian basin to the north (Baronnies) from the southern Provence Platform to the south [Arnaud, 1988; Ford and Stahel, 1995; Mascle and Vially, 1999]. Both cross sections suggest that the overall geometry of the Ventoux-Lure hanging wall consists of an ~5°S to 10°S dipping homocline formed of massive Early Cretaceous marine limestone (Figure 3). The Ventoux-Lure hanging wall is deformed by the Vaucluse Mounts anticline to the west and by the NNE trending Oligocene Sault graben in the center (Figures 1 and 4). The footwall of the Ventoux-Lure thrust corresponds to imbrications of closely spaced north verging thrusts and narrow asymmetric synclines filled by Oligocene-Miocene series (Figures 5c and 8). Preserved or tilted normal fault scarps are common between Mesozoic and Oligocene-Miocene series [Casagrande et al., 1989]. An Oligocene fault that cuts the Ventoux thrust shows major thrusting before the Oligocene; i.e., during the Pyrenean-Provence shortening (Figures 5c and 8). In part, the reactivation of the Ventoux thrust is post-Miocene, as revealed by the deformed Miocene series [Villegier and Andrieux, 1987].

The geology of the southern edge of the Baronnies basin is characterized by east trending fault-propagation folds and Jurassic-Early Cretaceous syn-sedimentary normal faults that were associated with

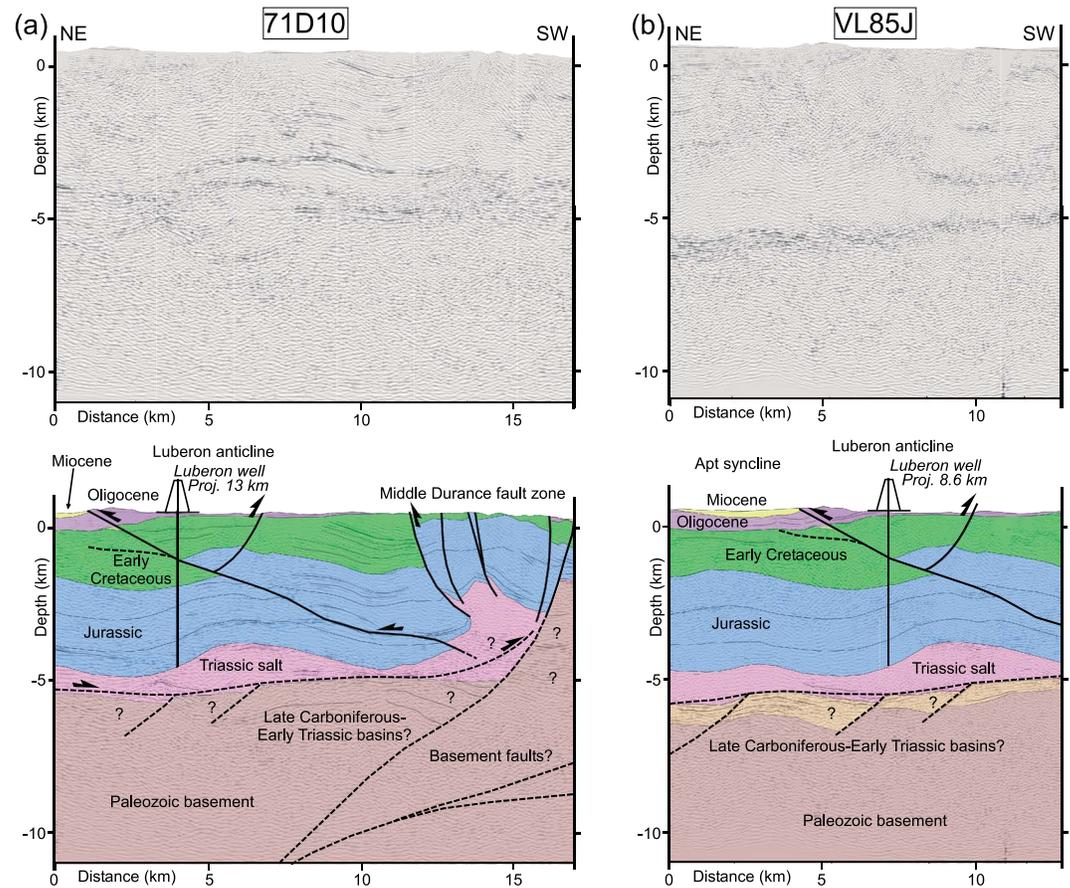


Figure 7. Interpretations of seismic profile (a) 71D10 and (b) VL85J across the eastern Luberon anticline and Middle Durance fault zone. For location, see Figures 1 and 3a (cross-section T1).

salt migration, like the Propiac diapir in cross section T2 [Casagrande *et al.*, 1989] (Figures 1 and 4). Cross-section balancing suggests that the thick Mesozoic sedimentary infilling of the southern edge of the Baronnies zone was expelled southward without basement-fault reactivation, as suggested by Roure and Colletta [1996] and Mascle and Vially [1999]. Shortening was accommodated southward by internal thrust folds and in the Ventoux-Lure thrust as an intercutaneous wedge (Figures 3 and 4). Thrusting activity occurred during the Lutetian-Bartonian, as revealed by locally preserved syntectonic conglomerates with growth-strata patterns [Montenat *et al.*, 2005] (Figure 1) and during the Neogene [Villegier and Andrieux, 1987; Casagrande *et al.*, 1989].

4.4. Campanian-Eocene Pyrenean-Provence Shortening Versus Oligocene Ligurian and Neogene Alpine Deformations

The Provence fold-and-thrust belt recorded superimposed deformations from the Campanian to the present day, due to the Pyrenean-Provence and Alpine compressions, and to the rifting of the Ligurian basin. Cross-sections T1 and T2 of Figures 3 and 4 are restored just after and before the Campanian-Eocene compression, i.e., Late Eocene and latest Santonian, respectively. Assuming that the top of the uppermost Santonian series was horizontal before the shortening, restoration allows modeling of the pre-tectonic basement geometry before the Campanian-Eocene Pyrenean-Provence compression. The Late Eocene restorations allow the precise quantification of the Pyrenean-Provence shortening and the geometry of the Provence Chain before the Oligocene Ligurian and Neogene Alpine deformations.

The restoration of cross-sections T1 and T2 at the end of the Eocene indicates that the post-Eocene to present-day horizontal tectonic movement is small, at about 1.5 km (Figures 3a and 4b). The Oligocene extension is associated with high-dipping normal to strike-slip faults, delimiting grabens and half

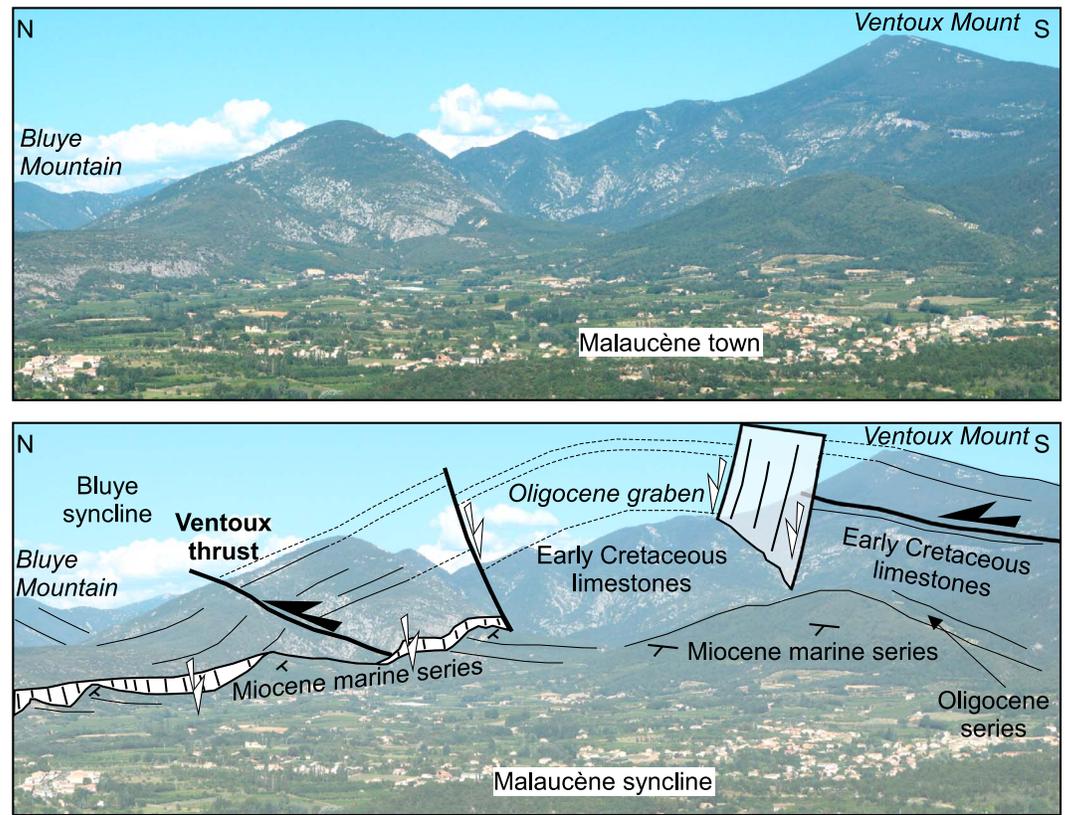


Figure 8. East looking panoramic view of the Ventoux thrust and Miocene Malaucène basin. The Ventoux thrust is cut by an Oligocene normal fault sealed by Miocene foresets [Casagrande et al., 1989]. This observation provides evidence for major prestructuring of Ventoux thrust during the Pyrenean-Provence compression. Bedding traces are enhanced by black lines. UTM31 view location: 667727; 4893779. For location, see also Figures 1, 4a (cross-section T2), and 5c.

grabens, and local migration of Triassic salt [Arnaud et al., 1990; Bestani et al., 2015] (Figures 5a and 5b). The Neogene Alpine deformation is minor and is associated with reactivated inherited strike-slip faults, thrusts, and folding in the western thin-skinned Provence domain [e.g., Champion et al., 2000; Molliex et al., 2011] (Figure 5c).

The total Pyrenean-Provence shortening ranges from 9.6 km (7.8%) in the west to 46.4 km (26%) in the east (sections T1 and T2, respectively; Figures 3b and 4b). The western thin-skinned Provence domain shows a homogeneous along-strike shortening of about 6 km to 7 km.

4.5. Kinematics of the Provence Thrust System

The development and evolution of the fold-and-thrust belts might be significantly controlled by upper crustal inheritance that developed during the contractional stage or continental rifting and the geometry of the preorogenic sedimentary wedge [e.g., Baby et al., 1989; Coward, 1996; Colletta et al., 1997; Ziegler et al., 1998; Kley and Monaldi, 2002; Lacombe and Mouthereau, 2002; Butler et al., 2006; Espurt et al., 2008]. The Provence foreland is characterized by contrasted Variscan and Mesozoic structural and sedimentary inheritances [Roure and Colletta, 1996; Bestani et al., 2015]. Extensional basement faults inherited from Late Carboniferous-Permian to Early Triassic times controlled the location of the deformation during the Pyrenean-Provence compression and the synchronous activity of some thrusts over a long period of time (up to ~40 Myr) [Espurt et al., 2012].

Structural inheritance in Provence accounts for significant along-strike variations, in terms of the structural architecture, tectonic style, and shortening (Figures 3 and 4). The difference in tectonic style and shortening between sections T1 and T2 might be accommodated by left-lateral strike-slip motion along the NE trending Aix-Middle Durance fault system south of the Valensole Plateau (Figure 1). Subsurface data and balanced

cross sections suggest that this fault system led to major thickness variations of the preorogenic Mesozoic pile between western and eastern Provence, due to the Mesozoic normal faulting (Figures 1, 3, and 4). No geological evidence that might support a Cenozoic reactivation of the deep Middle Durance basement fault is visible [Roure and Colletta, 1996]. This fault system had the role of an accommodation zone, in the sense of *Faulds and Varga* [1998], between the eastern thick-skinned domain and the western thin-skinned domain during the Pyrenean-Provence shortening. The footwall of the Aix-Middle Durance fault zone may have acted as a buttress to the N-S Pyrenean-Provence shortening [Andreani *et al.*, 2010], thus preventing the transfer of the thick-skinned shortening within the sedimentary cover of the western Provence. A small transfer of the thick-skinned shortening is only suspected in the Nerthe basement high [Tempier, 1987]. The shortening difference of 40 km observed in cross-section T1 in comparison with cross-section T2 might be also accommodated southward by thick-skinned basement thrusts that are now found in the offshore Ligurian basin and Sardinia [Tempier, 1987; Lacombe and Jolivet, 2005].

This along-strike structural behavior is also illustrated by the present-day compressional tectonic regime in Provence. West of the Middle Durance fault zone, most of the deep-seated seismic events related to the Alpine shortening are located near the basement-sedimentary cover interface (~8 km deep), which emphasizes the basement-cover detachment [Terrier *et al.*, 2008; Cushing *et al.*, 2008; Molliex *et al.*, 2011]. East of the Middle Durance fault zone, the existence of seismic events below the Valensole Plateau (Figure 1) at a similar depth as to the west demonstrates present-day tectonic strain within the basement.

5. Discussion: Reconstruction of the Provence Chain Evolution

Crustal structural inheritance can have major roles in the evolution of fold-and-thrust belts [Lacombe and Mouthereau, 2002; Butler *et al.*, 2006, and references therein; Espurt *et al.*, 2014; Bellahsen *et al.*, 2014]. Little is known about the influence in terms of the geometry and thermal heterogeneities of the Provence crust and the associated Sardinia crust to the south [Garibaldi *et al.*, 2010; Le Pichon *et al.*, 2010]. To evaluate and discuss the control of the deep processes on the structure, building, and evolution of the Provence Chain, we constructed a transorogenic (~400 km long) balanced cross-section T1' at the scale of the lithosphere along section T1, which included the geodynamic evolution of the Ligurian basin and Sardinia to the south (Figure 9a).

In our construction, the geometry of the continental and oceanic crusts in the Ligurian basin under the post-Messinian series is modeled using lateral seismic reflection data of Rollet *et al.* [2002] and Bache *et al.* [2010]. The geometry of Sardinia was simplified as a homogenous basement block that included the Mesozoic-Cenozoic sedimentary cover. On the basis of the above-mentioned deep geophysical data, along section T1 we calculated a present crustal area of ~3 052 km² for the Sardinia continental crust and ~4 513 km² for the Eurasian continental crust (Figure 9a).

The present-day geometry of the Eurasian continental crust is characterized by southward thinning, from ~35 km beneath the Baronnies basin to ~7 km beneath the north Ligurian basin passive margin (Figure 9a) [Jiménez-Munt *et al.*, 2003; Tesauro *et al.*, 2008; Garibaldi *et al.*, 2010]. This crustal thinning might result from the Oligocene rifting and drifting of the Ligurian basin (by more than 200 km) that was associated with the counterclockwise rotation of the Sardinia-Corsica block [Rollet *et al.*, 2002]. Similar thinning was observed west of the study area in the Gulf of Lion, by Séranne *et al.* [1995] and Benedicto *et al.* [1996] (Figure 2a). In contrast to the Gulf of Lion, onshore the Pyrenean basement thrusts were less reactivated in Provence area. Oligocene structures might be hidden under thick post-Messinian sequences of the Ligurian basin [Rollet *et al.*, 2002].

Three stages of deformation of the Provence Chain can be reconstructed from the Triassic to the Eocene, which are illustrated in Figure 9 and discussed below. In this sequential restoration, we balanced the crustal areas of Eurasia and Sardinia through consecutive deformational episodes according to the paleo-thicknesses and erosion of the sedimentary cover and basement units along the margins of the Ligurian basin [e.g., Jakni, 2000; Bestani, 2015; Malusà *et al.*, 2016].

1. *The Triassic stage* (post-Variscan structure): Late Paleozoic tectonic map reconstruction of Figure 2d shows that the Eurasia-Provence and Sardinia crusts were separated by a major east to NE trending dextral shear zone [Matte, 2001; Rossi *et al.*, 2009; Guillot and Menot, 2009]. This major deformation zone is interpreted as the eastern continuation of the North-Pyrenean Fault Zone between Eurasia and Sardinia [Lacombe and Jolivet, 2005]. Tectonic map reconstruction indicates a dextral strike-slip

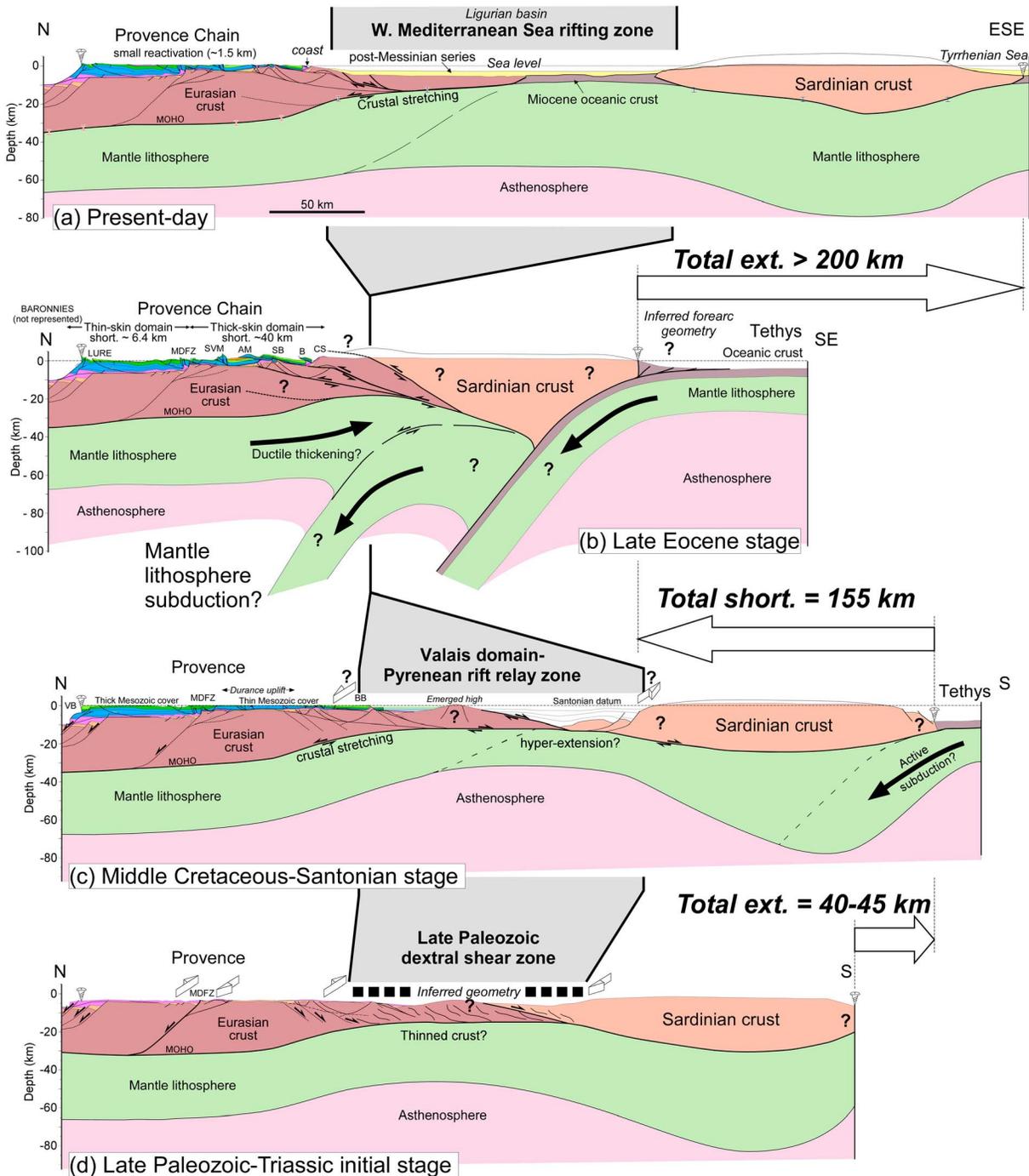


Figure 9. Lithospheric-scale balanced and restored cross-section T1' across the entire Pyrenean-Provence orogenic system along cross-section T1 and Sardinia. Crustal and lithosphere thickness determined by deep geophysical data from Jiménez-Munt *et al.* [2003] (black point), Tesauro *et al.* [2008], and Garibaldi *et al.* [2010]. See details in text and legend in Figure 3. For location, see Figure 2. MDFZ: Middle Durance fault zone. SVM: Sainte-Victoire Mountain. AM: Aurélien Mount. SB: Sainte-Baume. B: Bandol. CS: Cap Sicié. VB: Vocontian basin. DU: Durance uplift. BB: Beausset basin. Ext.: Extension. Short.: Shortening.

component of more than 300 km. Because this shear zone prevents precise reconstruction of the lithospheric-scale balanced cross section, we assume a simplified Triassic geometry for this deformation zone, which included surficial Late Carboniferous-Permian to Early Triassic half-grabens [Bestani *et al.*, 2015] and a thinned crust, probably associated with ductile deformations (Figure 9d).

2. *The Santonian stage* (post-Pyrenean rifting): According to Middle Cretaceous tectonic map reconstruction of Figure 2c [Advokaat et al., 2014], the restoration before the Pyrenean-Provence compression shows an ~140 km wide rift system with crustal hyperextension between Eurasia and Sardinia (Figure 9c). This modeled rifting zone can be interpreted as the relay zone between the Pyrenean rift and Valais domain [Stampfli et al., 1998; Rosenbaum et al., 2002; Bellahsen et al., 2014], although the age of the Valais domain is debated (middle to late Jurassic or/and early Cretaceous) [e.g., Beltrando et al., 2012, and references therein]. The Provence and Sardinia regions were uplifted and subject to major erosion associated with bauxites deposition since Albian and until the beginning of the Late Cretaceous (e.g., "Durance uplift"). Our reconstruction is consistent with the paleogeography of Hennuy [2003], which included basement high located close to sea level between the Provence and Sardinia. This massif constituted by Variscan rocks was eroded during the Middle Cretaceous-Santonian period, whence it fed terrigenous sediments at least into the Beausset basin in the north (Figure 9c).

In this rifting context, the restoration suggests extreme crustal thinning of the southern Provence crust between the underlying mantle lithosphere and the Mesozoic sedimentary cover. In contrast to the Pyrenees, the Provence rift shows no field evidence for mantle exhumation or ductile deformation at shallow crustal level [Duée et al., 1984; Roure et al., 1989; Specht, 1989; Lagabrielle et al., 2010; Clerc et al., 2012; Vacherat et al., 2014] because these inner features have been erased by the Oligocene Ligurian rifting and drifting. On the basis of our cross-section restoration and paleogeographic reconstruction (Figures 2 and 9c), the N-S total crustal extension achieved in this zone between the Triassic and Santonian is estimated to be at least of 40–45 km. This partitioned rift model, including a central basement high between Provence and Sardinia, is similar to that proposed in eastern and central Pyrenees between the North-Pyrenean Fault to the south and Eurasia to the north [Clerc and Lagabrielle, 2014]. The extension amount calculated for Provence rift is close to the minimum values (~50 km) estimated in the eastern and central Pyrenees by Vergés and García-Senz [2001] and Mouthereau et al. [2014], respectively.

3. *The Eocene stage* (post-Pyrenean-Provence compression): From north to south, the Eocene restoration shows that the Provence orogen was formed by an outer thin-skinned thrust system that deformed a thick Mesozoic sedimentary cover north of the Aix-Middle Durance fault system, an inner north verging thick-skinned system, and the Sardinia continental block bounded southward by the Tethys subduction system. As the Oligocene deformation in the outer Provence belt was small, the crustal geometry is similar to the present in this zone, although the inner basement thrust system thickened the crust to up to ~20 km (Figure 9b).

During the inversion process, we propose a tectonic model where the previously extended and thermally weakened area was sandwiched between Eurasia and Sardinia. In this model, the strong Eurasia lithosphere [Le Pichon et al., 2010] behaved as a lower tectonic wedge that indented the Sardinia continental block at the crust-mantle boundary [Roure et al., 2012]. We propose that the indentation of this lithospheric-scale tectonic wedge was accommodated by inversion of north verging crustal faults (e.g., Cap Sicié thrust), north directed subduction of the dense Sardinia mantle lithosphere under the Provence, and ductile thickening of the Provence mantle lithosphere (Figure 9b). This model does not involve the midcrustal detachment level as suggested previously by Vially and Trémolières [1996] across the entire Provence crust, but has crust/mantle interface detachment in the internal zone where the crustal thickness was reduced, and thrusts that cut through the crust of the Provence margin (Figures 9b and 9c) [Butler, 2013]. The small crustal volume of Sardinia prevents the construction of an alternative balanced cross section with underthrusting of crustal material of Sardinia beneath the Eurasian crust during the collision. However, the overthrusting of the Sardinia block on the Provence crust is consistent with apatite fission track data along the western margin of Sardinia, which recorded the Late Cretaceous-Eocene cooling ages [Malusà et al., 2016]. Our structural model, in which the crust is decoupled from the mantle lithosphere during the Pyrenean-Provence orogeny, is an efficient thickening mechanism that leads to the structural culmination of the inner thick-skinned Provence associated with a thin crust (Figure 9b).

Although the structural model illustrated in Figure 9 includes neither precise geometry of the Middle Cretaceous hyperextended rift system at depth nor the internal structure of the Sardinia block, we calculate a N-S total crustal shortening in this sector of the Provence Chain of ~155 km (~35%) over the Late Cretaceous-Eocene period (Figure 9b). This estimate of the Pyrenean-Provence contraction is a minimum value mainly because the original crustal thicknesses and rift geometry has to be better constrained. Most of this shortening

is accommodated in the internal basement imbrication of the thick-skinned Provence belt. Ductile Triassic evaporites and thick sedimentary cover in western Provence might have favored the thin-skinned tectonic style and transfer of compressional stress in the Baronnies zone up to 100 km away from the inner orogenic wedge (Figures 1 and 9). In contrast to the Pyrenees, which involved the stacking of at least three south verging crustal thrust sheets [e.g., Muñoz, 1992; Teixell *et al.*, 2016], the Provence Chain localized the overall crustal shortening along at least three north verging thrust sheets (Figure 9b). This northward structural stacking was controlled by inherited north dipping weakness zones in Provence margin related to the Late Paleozoic and Mesozoic rifting events and the high rigidity of the Variscan basement of Sardinia [Tesauro *et al.*, 2009; Rossi *et al.*, 2009]. However, these structures might have been removed by erosion or Neogene deformation.

The minimum crustal shortening amount (~155 km) across the Provence Chain is higher than the calculated ~95–100 km in the western Pyrenees [Teixell *et al.*, 2016], ~122–142 km [Mouthereau *et al.*, 2014] in the central Pyrenees and ~125 km [Vergés *et al.*, 1995] in the eastern Pyrenees for approximately the same period (Late Cretaceous-Eocene period). This eastward increase of the shortening amount might result from a higher amount of subduction in the Provence segment, which is consistent with counterclockwise rotation of the Sardinia block with respect to Iberia during the Pyrenean-Provence contractional period [Advokaat *et al.*, 2014].

6. Conclusions

Surface structural data, seismic profiles, exploration wells, and previously published deep geophysical data together with tectonic map reconstructions have been combined here with crustal-scale to lithospheric-scale structural balancing techniques. These have thus contributed to an understanding of the dynamics of the Provence Chain and its long-term history of deformation insight into the Pyrenean and Mediterranean geodynamics.

The construction of two crustal-scale sections (~120 km long) across the present Provence belt indicates various structural styles that include deep-seated basement faults that affect the entire crust, tectonic inversions of Paleozoic-Mesozoic basins, shallower décollements within sedimentary cover, and salt diapirism. The thrust belt is also characterized by heterogeneous shortening along the strike, accommodated by a regional accommodation zone, the Aix-Middle Durance fault system, overlying a Paleozoic basement grain.

Although Oligocene-Miocene rifting and Neogene Alpine compression led to additional structural complexity (including the Ligurian continental break-up and the counterclockwise rotation of the Sardinia-Corsica block), this deformation is small (1.5 km of horizontal tectonic movement) across the present Provence belt in comparison with the Pyrenean-Provence deformation (up to 46.4 km of shortening). Consequently, the major trend of the present-day tectonic framework of Provence belt results from the Late Cretaceous-Eocene compression.

The construction of a sequentially restored cross section across the Provence-Sardinia orogen (~400 km long) at the scale of the lithosphere suggests strong similarities between Provence and Pyrenean geodynamics. The Provence belt shows evidence for Middle Cretaceous rifting between Eurasia and Sardinia that links the Pyrenean rift to the west and the Valais domain to the northeast. Restoration suggests a partitioned rift system with crustal hyperextension. The total crustal extension achieved in this zone is estimated at least of 40–45 km. During Late Cretaceous-Eocene inversion, the Eurasian lithosphere formed a rigid indent into the Sardinia lithosphere at the crust-mantle boundary. This shortening was accommodated by inversion of north verging inherited crustal faults and north directed subduction of the Sardinia mantle lithosphere under the Provence associated with ductile thickening of the Provence mantle lithosphere. The total crustal shortening in the Provence segment reaches ~155 km (35%). This value is higher than in the Pyrenees for the same period. It might result from an eastward increase in the amount of subduction associated with counterclockwise rotation of the Sardinia with respect to Iberia during the Pyrenean-Provence compression.

This study shows the prime control of the Variscan structural inheritance over a long period of time on the tectonic evolution of a geological system, the Provence orogen. This includes mechanical heterogeneities, such as Late Paleozoic rift structures and shear zones, reactivated during Middle Cretaceous rifting between Eurasia and Sardinia. In domains where Mesozoic rifting is well marked, inherited basement normal faults and the weak crust favored the formation of an inner thick-skinned thrust belt during Late Cretaceous-Eocene contraction. During the Oligocene, these domains were still predisposed for the localized faulting of the Ligurian basin rifting and the seafloor spreading between Provence and Sardinia.

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References

- Advokaat, E. L., D. J. J. van Hinsbergen, M. Maffione, C. G. Langereis, R. L. M. Vissers, A. Cherchi, R. Schroeder, H. Madani, and S. Columbu (2014), Eocene rotation of Sardinia, and the paleogeography of the western Mediterranean region, *Earth Planet. Sci. Lett.*, *401*, 183–195, doi:10.1016/j.epsl.2014.06.012.
- Andreani, L., N. Loget, C. Rangin, and X. L. Pichon (2010), New structural constraints on the southern Provence thrust belt (France): Evidence for a Eocene shortening event linked to the Corsica–Sardinia subduction, *Bull. Soc. Geol. Fr.*, *181*, 547–563, doi:10.2113/gssgfbull.181.6.547.
- Angelier, J., and J. Aubouin (1976), Contribution à l'étude géologique des bandes triasiques provençales: De Barjols (Var) au bas Verdon, *Bull. Bur. Rech. Geol. Min., Sect. I*, *3*, 187–217.
- Arnaud, H. (1988), Subsidence in certain domains of south-eastern France during the Ligurian Thetys opening and spreading stages, *Bull. Soc. Geol. Fr.*, *8(4)*, 725–732.
- Arnaud, M., B. Beaudoin, E. Colomb, and C. Monleau (1990), Le gypse triasique de la vallée de l'Huveaune (Bouches-du-Rhône) a été karstifié pendant le Crétacé supérieur. Implications tectoniques, *Géol. Alp.*, *66*, 117–121.
- Arthaud, F., and P. Matte (1975), Les décrochements tardi-hercyniens du sud-ouest de l'Europe. Géométrie et essai de reconstitution des conditions de la déformation, *Tectonophysics*, *25*, 139–171, doi:10.1016/0040-1951(75)90014-1.
- Baby, P., G. Hérail, J. M. Lopez, O. Lopez, J. Oller, J. Pareja, T. Sempere, and D. Tufino (1989), Structure de la zone subandine de Bolivie: Influence de la géométrie des séries sédimentaires antéorogéniques sur la propagation des chevauchements, *C. R. Acad. Sci., Ser. II*, *309*, 1717–1722.
- Bache, F., J. L. Olivet, C. Gorini, D. Aslanian, C. Labails, and M. Rabineau (2010), Evolution of rifted continental margins: The case of the Gulf of Lions (Western Mediterranean Basin), *Earth Planet. Sci. Lett.*, *292*, 345–356.
- Bellahsen, N., F. Mouthereau, A. Boutoux, M. Bellanger, O. Lacombe, L. Jolivet, and Y. Rolland (2014), Collision kinematics in the western external Alps, *Tectonics*, *33*, 1055–1088, doi:10.1002/2013TC003453.
- Beltrando, M., G. Frasca, R. Compagnoni, and A. Vitale-Brovarone (2012), The Valaisan controversy revisited: Multi-stage folding of a Mesozoic hyper-extended margin in the Petit St. Bernard pass area (Western Alps), *Tectonophysics*, *579*, 17–36, doi:10.1016/j.tecto.2012.02.010.
- Benedicto, A., P. Labaume, M. Séguret, and M. Séranne (1996), Low-angle crustal ramp and basin geometry in the Gulf of Lion passive margin: Oligocene-Aquitainian Vistrenque graben, SE France, *Tectonics*, *15*, 1192–1212, doi:10.1029/96TC01097.
- Bergerat, F. (1987), Stress fields in the European platform at the time of Africa-Eurasia collision, *Tectonics*, *6*, 99–132, doi:10.1029/TC006i002p00099.
- Besson, D. (2005), Architecture du bassin rhodano-provençal miocène (Alpes, SE France), Relations entre déformation, physiographie et sédimentation dans un bassin molassique d'avant-pays, PhD thesis, 438 pp., Ecole des Mines de Paris.
- Bestani, L. (2015), Géométrie et cinématique de l'avant-pays provençal: Modélisation par coupes équilibrées dans une zone à tectonique polyphasée, PhD thesis, 250 pp., Aix-Marseille Univ.
- Bestani, L., N. Espurt, J. Lamarche, M. Floquet, J. Philip, O. Bellier, and F. Hollender (2015), Structural style and evolution of the Pyrenean-Provence thrust belt, SE France, *Bull. Soc. Geol. Fr.*, *186*, 223–241.
- Boyer, S. E., and D. Elliott (1982), The geometry of thrust systems, *Am. Assoc. Pet. Geol. Bull.*, *66*, 1196–1230.
- Burg, J. P., J. P. Brun, and J. van den Driessche (1990), Le Sillon Houiller du Massif Central français: Faille de transfert pendant l'amincissement crustal de la chaîne varisque?, *C. R. Acad. Sci.*, *311*, 147–152.
- Busulini, A., I. Dieni, F. Massari, D. Pejović, and J. Wiedmann (1984), Nouvelles données sur le Crétacé Supérieur de la Sardaigne Orientale, *Cretaceous Res.*, *5*, 243–258.
- Butler, R. W. H. (2013), Area balancing as a test of models for the deep structure of mountain belts, with specific reference to the Alps, *J. Struct. Geol.*, *52*, 2–16.
- Butler, R. W. H., E. Tavarnelli, and M. Grasso (2006), Structural inheritance in mountain belts: An Alpine-Apennine perspective, *J. Struct. Geol.*, *28(11)*, 1893–1908.
- Carosi, R., C. Frassi, D. Iacopini, and C. Montomoli (2005), Post collisional transpressive tectonics in northern Sardinia (Italy), *J. Virtual Explor.*, *19*, Paper 3.
- Casagrande, L., J. Andrieux, and J. L. Morel (1989), Le massif de Suzette (Vaucluse): L'inversion tectonique d'un graben oligocène, *Geol. Fr.*, *3*, 3–12.
- Champion, C., P. Choukroune, and G. Clauzon (2000), La déformation post-Miocène en Provence occidentale, *Geodin. Acta*, *13*, 67–85, doi:10.1016/S0985-3111(00)00114-5.
- Cherchi, A., N. Mancin, L. Montadert, M. Murrù, M. Terasa Putzu, F. Schiavinotto, and V. Verrubbi (2008), Les conséquences stratigraphiques de l'extension oligo-miocène en Méditerranée occidentale à partir d'observations dans le système de grabens de Sardaigne (Italie), *Bull. Soc. Geol. Fr.*, *179*, 267–287.
- Chorowicz, J., and A. Mekarnia (1992), Evidence of a NW-SE striking Albo-Aptian extensional event in Provence (southeastern France), *C. R. Acad. Sci. Paris*, *315*, 861–866.
- Choukroune, P., B. Pinet, F. Roue, and M. Cazes (1990), Major Hercynian thrust along the ECORS Pyrenees and Biscay lines, *Bull. Soc. Geol. Fr.*, *2*, 313–320, doi:10.2113/gssgfbull.VI.2.313.
- Clauzon, G., and C. Gouvernet (1973), Sur la présence d'une brèche syn-orogénique d'âge paléogène dans le chaînon du Petit Luberon (Vaucluse), *C. R. Acad. Sci. Paris*, *277(D)*, 2637–2640.
- Clauzon, G., J.-P. Suc, F. Gautier, A. Berger, and M.-F. Loutre (1996), Alternate interpretation of the Messinian salinity crisis: Controversy resolved? *Geology*, *24*, 363–366, doi:10.1130/0091-7613(1996)024<0363:AIOTMS>2.3.CO;2.
- Clauzon, G., T.-J. Fleury, O. Bellier, S. Molliex, L. Mocochain, and J.-P. Aguilar (2011), Morphostructural evolution of the Luberon since the Miocene (SE France), *Bull. Soc. Geol. Fr.*, *182*, 95–110.
- Clerc, C., and Y. Lagabrielle (2014), Thermal control on the modes of crustal thinning leading to mantle exhumation: Insights from the Cretaceous Pyrenean hot paleomargins, *Tectonics*, *33*, 1340–1359, doi:10.1002/2013TC003471.
- Clerc, C., Y. Lagabrielle, M. Neumaier, J.-Y. Reynaud, and M. de Saint Blanquat (2012), Exhumation of subcontinental mantle rocks: Evidence from ultramafic-bearing clastic deposits nearby the Lherz peridotite body, French Pyrenees, *Bull. Soc. Geol. Fr.*, *183(5)*, 443–459.
- Colletta, B., F. Roue, B. de Toni, D. Loureiro, H. Passalacqua, and Y. Gou (1997), Tectonic inheritance, crustal architecture, and contrasting structural styles in the Venezuela Andes, *Tectonics*, *16*, 777–794, doi:10.1029/97TC01659.
- Corroy, G., and J. Philip (1964), Le brachyanticlinal des pics des Corbeaux, dans le massif de la Sainte-Baume (Var), *Bull. Soc. Geol. Fr.*, *7*, 560–563.
- Coward, M. P. (1996), Balancing sections through inverted basins, in *Modern Developments in Structural Interpretation, Validation and Modelling*, edited by P. G. Buchanan and D. A. Neuiwand, *Geol. Soc. London Spec. Publ.*, *99*, 51–77.

- Cushing, E. M., O. Bellier, S. Nechtschein, M. Sébrier, A. Lomax, P. Volant, P. Dervin, P. Guignard, and L. Bove (2008), A multidisciplinary study of a slow-slipping fault for seismic hazard assessment: The example of the Middle Durance Fault (SE France), *Geophys. J. Int.*, *172*, 1163–1178, doi:10.1111/j.1365-246X.2007.03683.x.
- Dahlstrom, C. D. A. (1969), Balanced cross-sections, *Can. J. Earth Sci.*, *6*(4), 743–757.
- Danišik, M., J. Kuhlemann, I. Dunkl, B. Székely, and W. Frisch (2007), Burial and exhumation of Corsica (France) in the light of fission track data, *Tectonics*, *26*, TC1001, doi:10.1029/2005TC001938.
- Debroas, E. J. (1990), Le Flysch noir albo-cénomanién témoin de la structuration albienne à sénonienne de la Zone nord-pyrénéenne en Bigorre (Hautes-Pyrénées, France), *Bull. Soc. Geol. Fr.*, *8*, 273–285.
- de Graciansky, P. C., and M. Lemoine (1988), Early Cretaceous tectonics in the southwestern French Alps: A consequence of North Atlantic rifting during Tethyan spreading, *Bull. Soc. Geol. Fr.*, *5*, 733–737.
- Delfaud, J., N. Toutin-Morin, and R. Morin (1989), Un cône alluvial en bordure d'un bassin intramontagneux: La formation permienne du Rocher de Roquebrune (Bassin du Bas-Argens, Provence orientale), *C. R. Acad. Sci., Ser. II: Mec., Phys., Chim., Sci. Terre Univers*, *309*, 1811–1817.
- Demory, F., G. Conesa, J. Oudet, H. Mansouri, P. Münch, J. Borgomano, N. Thouveny, J. Lamarche, F. Gisquet, and L. Marié (2011), Magnetostratigraphy and paleoenvironments in shallow-water carbonates: The Oligocene-Miocene sediments of the northern margin of the Liguro-Provençal basin (West Marseille, southeastern France), *Bull. Soc. Geol. Fr.*, *182*, 37–55.
- Desegaulx, P., F. Roure, and A. Villein (1990), Structural evolution of the Pyrenees: Tectonic inheritance and flexural behaviour in the continental crust, *Tectonophysics*, *182*(3–4), 211–225, doi:10.1016/0040-1951(90)90164-4.
- Dèzes, P., S. M. Schmid, and P. A. Ziegler (2004), Evolution of the European Cenozoic rift system: Interaction of the Alpine and Pyrenean orogens with their foreland lithosphere, *Tectonophysics*, *389*, 1–33, doi:10.1016/j.tecto.2004.06.011.
- Dubois, P. (1966), Sur la sédimentation et la tectonique du Miocène de la Provence occidentale, *Bull. Soc. Geol. Fr.*, *7*, 793–801.
- Duée, G., Y. Lagabrielle, A. Coutelle, and A. Fortané (1984), Les Iherzolithes associées aux Chaînons Béarnais (Pyrénées Occidentales): Mise à l'affleurement anté-dogger et résédimentation albo-cénomaniénne, *C. R. Acad. Sci., Ser. II*, *299*, 1205–1209.
- Dufaure, P., J. Ferrat, A. Laumondais, and M. Mille (1969), Description sommaire d'un sondage dans la chaîne de Martigues (Bouches-du-Rhône), *Bull. Soc. Geol. Fr.*, *5*, 670–675.
- Espurt, N., S. Brusset, P. Baby, W. Hermoza, R. Bolaños, D. Uyen, and J. Déramond (2008), Paleozoic structural controls on shortening transfer in the Subandean foreland thrust system, Ene and southern Ucayali basins, Peru, *Tectonics*, *27*, TC3009, doi:10.1029/2007TC002238.
- Espurt, N., J.-C. Hippolyte, M. Saillard, and O. Bellier (2012), Geometry and kinematic evolution of a long-living foreland structure inferred from field data and cross section balancing, the Sainte-Victoire System, Provence, France, *Tectonics*, *31*, TC4021, doi:10.1029/2011TC002988.
- Espurt, N., J.-C. Hippolyte, N. Kaymakci, and E. Sangu (2014), Lithospheric structural control on inversion of the southern margin of the Black Sea Basin, Central Pontides, Turkey, *Lithosphere*, *6*, 26–34, doi:10.1130/L316.1.
- Faulds, J. E., and R. J. Varga (1998), The role of accommodation zones and transfer zones in the regional segmentation of extended terranes, in *Accommodation Zones and Transfer Zones; the Regional Segmentation of the Basin and Range Province*, *Geol. Soc. Am. Spec. Pap.*, *323*, 1–45.
- Fellin, M. G., V. Picotti, and M. Zattin (2005), Neogene to Quaternary rifting and inversion in Corsica: Retreat and collision in the western Mediterranean, *Tectonics*, *24*, TC1011, doi:10.1029/2003TC001613.
- Ford, M., and U. Stahel (1995), The geometry of a deformed carbonate slope-basin transition: The Ventoux-Lure fault zone, SE France, *Tectonics*, *14*, 1393–1410, doi:10.1029/95TC02522.
- Garibaldi, C., L. Guillou-Frotier, J.-M. Lardeaux, D. Bonte, S. Lopez, V. Bouchot, and P. Ledru (2010), Thermal anomalies and geological structures in the Provence Basin; implications for hydrothermal circulations at depth, *Bull. Soc. Geol. Fr.*, *181*, 363–376.
- Gattacceca, J., A. Deino, R. Rizzo, D. S. Jones, B. Henry, B. Beauvoisin, and F. Vadeboin (2007), Miocene rotation of Sardinia: New paleomagnetic and geochronological constraints and geodynamic implications, *Earth Planet. Sci. Lett.*, *258*, 359–377, doi:10.1016/j.epsl.2007.02.003.
- Guieu, G. (1973), L'évolution tectonique de la chaîne de la Nerthe, au Nord-Ouest de Marseille, *C. R. Acad. Sci. Paris*, *276*, 13–16.
- Guieu, G., and J. Roussel (1990), Arguments for the pre-rift uplift and rift propagation in the Ligurian-Provençal Basin (northwestern Mediterranean) in the light of Pyrenean Provençal Orogeny, *Tectonics*, *9*, 1113–1142, doi:10.1029/TC009i005p01113.
- Guignard, P., O. Bellier, and D. Chardon (2005), Géométrie et cinématique post-oligocène des failles d'Aix et de la moyenne Durance (Provence, France), *C. R. Acad. Sci. Geosci.*, *337*, 375–384.
- Guillot, S., and R.-P. Menot (2009), Paleozoic evolution of the External Crystalline Massifs of the Western Alps, *C. R. Geosci.*, *341*, 253–265.
- Guyonnet-Benaize, C. (2011), Modélisation 3D multi-échelle des structures géologiques de la région de la faille de la moyenne Durance (SE France), Thèse Sci., 187 pp., Aix-Marseille Univ., Centre Saint-Charles, Marseille.
- Guyonnet-Benaize, C., J. Lamarche, J.-P. Masse, M. Villeneuve, and S. Viseur (2010), 3D structural modelling of small-deformations in poly phase faults pattern, application to the Mid-Cretaceous Durance uplift, Provence (SE France), *J. Geodyn.*, *50*, 81–93, doi:10.1016/j.jog.2010.03.003.
- Guyonnet-Benaize, C., J. Lamarche, F. Hollender, S. Viseur, P. Münch, and J. Borgomano (2015), Three-dimensional structural modeling of an active fault zone based on complex outcrop and subsurface data: The Middle Durance Fault Zone inherited from polyphase Mesozoic tectonics (southeastern France), *Tectonics*, *34*, 265–289, doi:10.1002/2014TC003749.
- Handy, M. R., S. M. Schmid, R. Bousquet, E. Kissling, and D. Bernoulli (2010), Reconciling plate-tectonic reconstructions of Alpine Tethys with the geological-geophysical record of spreading and subduction in the Alps, *Earth Sci. Rev.*, *102*(3–4), 121–158, doi:10.1016/j.earscirev.2010.06.002.
- Hennuy, J. (2003), Sédimentation carbonate et silicoclastique sous contrôle tectonique, le bassin sud-provençal et sa plate-forme carbonatée du Turonien au Coniacien moyen. Evolution séquentielle, diagénétique, paléogéographique, Thèse Sci., 252 pp., Aix-Marseille Univ., Centre Saint-Charles, Marseille.
- Hippolyte, J.-C., J. Angelier, F. Bergerat, D. Nury, and G. Guieu (1993), Tectonic-stratigraphic record of paleostress time changes in the Oligocene basins of the Provence, southern France, *Tectonophysics*, *226*, 15–35, doi:10.1016/0040-1951(93)90108-V.
- Homberg, C., Y. Schnyder, and M. Benzaggagh (2013), Late Jurassic-Early Cretaceous faulting in the Southeastern French basin: Does it reflect a tectonic reorganization? *Bull. Soc. Geol. Fr.*, *184*, 501–514.
- Jakni, B. (2000), Thermochronologie par traces de fission des marges conjuguées du bassin liguro-provençal: la Corse et le massif des Maures-Tanneron, Thesis, 344 pp., Univ. de Grenoble I.
- Jammes, S., G. Manatschal, L. Lavier, and E. Masini (2009), Tectonosedimentary evolution related to extreme crustal thinning ahead of a propagating ocean: Example of the western Pyrenees, *Tectonics*, *28*, TC4012, doi:10.1029/2008TC002406.
- Jannin, S. (2011), Rôle de la Tectonique Salifère dans la Structuration du Bassin du Sud-Est (SE de la France): Définition d'un Modèle de Tectonique Salifère d'Après l'Etude du Secteur de Draguignan et Comparaison de ce Modèle aux Structures Halocinétiques Rencontrées sur l'Ensemble du bassin, *Mém. d'Ing. Géol.*, n° 476, 97 pp., 50 fig., 4 annexes, Inst. Polytech Lasalle Beauvais, Beauvais, France.

- Jiménez-Munt, I., R. Sabadini, A. Gardi, and G. Blanco (2003), Active deformation in the Mediterranean from Gibraltar to Anatolia inferred from numerical modelling and geodetic and seismological data, *J. Geophys. Res.*, *108*(B1), 2006, doi:10.1029/2001JB001544
- Kley, J., and C. R. Monaldi (2002), Tectonic inversion in the Santa Barbara System of the central Andean foreland thrust belt, northwestern Argentina, *Tectonics*, *21*(6), 1061, doi:10.1029/2002TC902003.
- Lacombe, O., and L. Jolivet (2005), Structural and kinematic relationships between Corsica and the Pyrenees-Provence domain at the time of the Pyrenean orogeny, *Tectonics*, *24*, TC1003, doi:10.1029/2004TC001673.
- Lacombe, O., and F. Mouthereau (2002), Basement-involved shortening and deep detachment tectonics in forelands of orogens: Insights from recent collision belts (Taiwan, Western Alps, Pyrenees), *Tectonics*, *21*(4), 1030, doi:10.1029/2001TC901018.
- Lacombe, O., J. Angelier, and P. Laurent (1992), Determining paleostress orientations from faults and calcite twins: A case study near the Sainte-Victoire Range (southern France), *Tectonophysics*, *201*, 141–156, doi:10.1016/0040-1951(92)90180-E.
- Lagabrielle, Y., P. Labaume, and M. de Saint Blanquat (2010), Mantle exhumation, crustal denudation, and gravity tectonics during Cretaceous rifting in the Pyrenean realm (SW Europe): Insights from the geological setting of the Iherzolite bodies, *Tectonics*, *29*, TC4012, doi:10.1029/2009TC002588.
- Leleu, S., J.-F. Ghienne, and G. Manatschal (2009), Alluvial fan development and morpho-tectonic evolution in response to contractional fault reactivation (Late Cretaceous–Palaeocene), Provence, France, *Basin Res.*, *21*(2), 157–187.
- Léonide, P., J. Borgomano, J.-P. Masse, and S. Doublet (2012), Relation between stratigraphic architecture and multi-scale heterogeneities in carbonate platforms: The Barremian-lower Aptian of the Monts de Vaucluse, SE France, *Sediment. Geol.*, *265–266*, 87–109, doi:10.1016/j.sedgeo.2012.03.019.
- Le Pichon, X., C. Rangin, Y. Hamon, N. Loget, J. Y. Lin, L. Andreani, and N. Flotte (2010), Geodynamics of the France Southeast Basin, *Bull. Soc. Geol. Fr.*, *181*, 477–501, doi:10.2113/gssgfbull.181.6.477.
- Lucazeau, F., and D. Mailhe (1986), Heat flow, heat production and fission track data from the hercynian basement around the Provençal Basin (Western Mediterranean), *Tectonophysics*, *128*, 335–356, doi:10.1016/0040-1951(86)90300-8.
- Malusà, M. G., M. Danišik, and J. Kuhlemann (2016), Tracking the Adriatic-slab travel beneath the Tethyan margin of Corsica-Sardinia by low-temperature thermochronometry, *Gondwana Res.*, *31*, 135–149, doi:10.1016/j.gr.2014.12.011.
- Mameli, P., G. Mongelli, G. Oggiano, and E. Dinelli (2007), Geological, geochemical and mineralogical features of some bauxite deposits from Nurra (western Sardinia, Italy): Insights on conditions of formation and parental affinity, *Int. J. Earth Sci.*, *96*, 887–902.
- Masclé, A., and R. Vially (1999), The petroleum systems of the Southeast Basin and Gulf of Lion (France), in *The Mediterranean Basins: Tertiary Extension Within the Alpine Orogen*, Spec. Publ., vol. 156, edited by B. Durand et al., pp. 121–140, Geol. Soc., London.
- Masse, J.-P., and J. Philip (1976), Paléogéographie et tectonique du Crétacé moyen en Provence, *Rev. Geogr. Phys. Geol. Dyn.*, *2*, 49–66.
- Mattauer, M., and F. Proust (1967), L'évolution structurale de la partie est du domaine pyrénéo-provençal au Crétacé et au Paléogène. Biogéographie du Crétacé–Éocène de la France méridionale, in *C.R. Coll. Biogéographie du Crétacé–Éocène de la France méridionale*, pp. 9–20, Travaux Lab. Géoch. Biosphère. Ecole Prat. Hautes Etudes, Paris.
- Matte, P. (2001), The Variscan collage and orogeny (480 ± 290 Ma) and the tectonic definition of the Armorica microplate: A review, *Terra Nova*, *13*, 122–128.
- Ménard, G. (1980), Profondeur du socle antétriasique dans le Sud-Est de la France, *C. R. Acad. Sci. Paris*, *290*, 299–302.
- Molli, G., and J. Malavielle (2011), Orogenic processes and the Corsica/Apennines geodynamic evolution: Insights from Taiwan, *Int. J. Earth Sci.*, *100*, 1207–1224, doi:10.1007/s00531-010-0598-y.
- Molliex, S., O. Bellier, M. Terrier, J. Lamarche, G. Martelet, and N. Espurt (2011), Tectonic and sedimentary inheritance on the structural framework of Provence (SE France): Importance of the Salon-Cavaillon Fault, *Tectonophysics*, *501*, 1–16.
- Montenat, C., P. Ott d'Estevou, and M. Saillard (1986), Sur la tectonique anté-cénomaniennne du fossé de Sault-de-Vaucluse (chaînes subalpines méridionales), *C. R. Acad. Sci. Paris*, *303*, 609–612.
- Montenat, C., M.-C. Janin, and P. Barrier (2004), L'accident du Toulourenc: Une limite tectonique entre la plate-forme provençale et le Bassin vocontien à l'Aptien–Albien (SE France), *C. R. Geosci.*, *336*, 1301–1310.
- Montenat, C., P. Barrier, and C. Hibschi (2005), Enregistrement des événements pyrénéo-provençaux dans les chaînes subalpines méridionales (Baronnies, France). Sédimentation continentale et tectonique éocènes, *Geol. Fr.*, *1*, 23–73.
- Morillon, A. C. (1997), Etude thermo-chronométrique appliquée aux exhumations en contexte orogénique: Le Massif des Maures (France), et les Cordillères Bétiques (Espagne), PhD thesis, 303 pp., Univ. De Nice, Nice, France.
- Mouthereau, F., P.-Y. Filleaudeau, A. Vacherat, R. Pík, O. Lacombe, M. G. Fellin, S. Castellort, F. Christophoul, and E. Masini (2014), Placing limits to shortening evolution in the Pyrenees: Role of margin architecture and implications for the Iberia/Europe convergence, *Tectonics*, *33*, 2283–2314, doi:10.1002/2014TC003663.
- Muñoz, J. A. E. (1992), Evolution of a continental collision belt: ECORS-Pyrenees crustal balanced cross-section, in *Thrust Tectonics*, edited by K. McClay, pp. 235–246, Chapman and Hall, London.
- Onézime, J., M. Faure, and G. Crévola (1999), Étude pétro-structurale du complexe granitique Rouet-Plan-de-la-Tour (massifs des Maures et du Tanneron occidental, Var), *C. R. Acad. Sci., Ser. IIA, Earth Planet. Sci.*, *328*, 773–779, doi:10.1016/S1251-8050(99)80170-0.
- Oudet, J., P. Munch, J. Borgomano, F. Quillevère, M. C. Melinte-Dobrinescu, F. Demory, S. Viseur, and J.-J. Cornée (2010), Land and sea study of the northeastern Golfe du Lion rifted margin; the Oligocene-Miocene of southern Provence (Nerthe area, SE France), *Bull. Soc. Geol. Fr.*, *181*, 591–607.
- Philip, J. (1970), Les formations calcaires à rudistes du Crétacé supérieur provençal et rhodanien, Thèse Sci., 438 pp., Univ. de Provence, Marseille.
- Philip, J., and J. Allemann (1982), Comparaison entre les plates-formes du Crétacé Supérieur de Provence et Sardaigne, *Cretaceous Res.*, *3*, 35–45.
- Philip, J., J.-P. Masse, and L. Machhour (1987), L'évolution paléogéographique et structurale du front de chevauchement nord-toulonnais (Basse-Provence occidentale, France), *Bull. Soc. Geol. Fr.*, *8*(III), 541–550.
- Rangin, C., X. Le Pichon, Y. Hamon, N. Loget, and A. Crespy (2010), Gravity tectonics in the SE Basin (Provence, France) imaged from seismic reflection data, *Bull. Soc. Geol. Fr.*, *181*, 503–530.
- Rolland, Y., M. Corsini, and A. Demoux (2009), Metamorphic and structural evolution of the Maures-Tanneron massif (SE Variscan chain): Evidence of doming along a transpressional margin, *Bull. Soc. Geol. Fr.*, *180*, 217–230, doi:10.2113/gssgfbull.180.3.217.
- Rollet, N., J. Déverchère, M.-O. Beslier, P. Guennoc, J.-P. Réhault, M. Sosson, and C. Truffert (2002), Back-arc extension, tectonic inheritance, and volcanism in the Ligurian Sea, Western Mediterranean, *Tectonics*, *21*(3), 1015, doi:10.1029/2001TC900027.
- Rosenbaum, G., G. S. Lister, and C. Duboz (2002), Relative motions of Africa, Iberia and Europe during Alpine orogeny, *Tectonophysics*, *359*(1–2), 117–129, doi:10.1016/S0040-1951(02)00442-0.
- Rossi, P., G. Oggiano, and A. Cocherie (2009), A restored section of the “southern Variscan realm” across the Corsica-Sardinia microcontinent, *C. R. Geosci.*, *341*, 224–238.

- Roure, F., and B. Colletta (1996), Cenozoic inversion structures in the foreland of the Pyrenees and Alps, in *Peri-Tethys Memoir 2: Structure and Prospects of Alpine Basins and Forelands*, *Mem. du Mus. Natl. Hist. Nat.* 170, edited by P. A. Ziegler, pp. 173–209, Mus. Natl. Hist. Nat., Paris.
- Roure, F., P. Choukroune, X. Berastegui, J. A. Muñoz, A. Villien, P. Matheron, M. Bareyt, M. Séguret, P. Camara, and J. Déramond (1989), ECORS deep seismic data and balanced cross sections: Geometric constraints on the evolution of the Pyrenees, *Tectonics*, 8, 41–50, doi:10.1029/TC008i001p00041.
- Roure, F., J.-P. Brun, B. Colletta, and J. Van Den Driessche (1992), Geometry and kinematics of extensional structures in the alpine foreland basin of southeastern France, *J. Struct. Geol.*, 14, 503–519, doi:10.1016/0191-8141(92)90153-N.
- Roure, F., P. Casero, and B. Addoum (2012), Alpine inversion of the North African margin and delamination of its continental lithosphere, *Tectonics*, 31, TC3006, doi:10.1029/2011TC002989.
- Schettino, A., and E. Turco (2011), Tectonic history of the western Tethys since the Late Triassic, *Geol. Soc. Am. Bull.*, 123, 89–105, doi:10.1130/B30064.1.
- Schreiber, D., G. Giannerini, and J. M. Lardeaux (2011), The Southeast France basin during Late Cretaceous times: The spatiotemporal link between Pyrenean collision and Alpine subduction, *Geodin. Acta*, 24, 21–35.
- Séguret, M. (1972), *Etude Tectonique des Nappes et Series Décollées de la Partie Centrale du Versant sud des Pyrénées*, Sér. Géol. Struct. n° 2, USTELA, Montpellier, France.
- Séranne, M., A. Benedicto, P. Labaume, C. Truffert, and G. Pascal (1995), Structural style and evolution of the Gulf of Lion Oligo-Miocene rifting: Role of the Pyrenean orogeny, *Mar. Pet. Geol.*, 12, 809–820, doi:10.1016/0264-8172(95)98849-Z.
- Shaw, J., C. Connors, and J. Suppe (2005), Seismic interpretation of contractional fault-related folds, in *AAPG Seismic Atlas*, *Stud. Geol.*, vol. 53, pp. 1–156, Am. Assoc. of Pet. Geol., Tulsa, Okla.
- Specht, M. (1989), *Tectonique de chevauchement le long du profil ECORS-Pyrénées: un modèle d'évolution de prisme d'accrétion continental*, PhD thesis, 99, 353 pp., Univ. de Bretagne Occident. de Brest (Sci.).
- Stampfli, G. M., J. Mosar, D. Marquer, R. Marchant, T. Baudin, and G. Borel (1998), Subduction and obduction processes in the Swiss Alps, *Tectonophysics*, 296, 159–204.
- Suppe, J. (1983), Geometry and kinematics of fault-bend folding, *Am. J. Sci.*, 283, 684–721.
- Suppe, J., and D. A. Medwedeff (1990), Geometry and kinematics of fault-propagation folding, *Ecolgae Geol. Helv.*, 83(3), 409–454.
- Teixell, A., P. Labaume, and Y. Lagabrielle (2016), The crustal evolution of the west-central Pyrenees revisited: Inferences from a new kinematic scenario, *C. R. Geosci.*, doi:10.1016/j.crte.2015.10.010, in press.
- Tempier, C. (1987), Modèle nouveau de mise en place des structures provençales, *Bull. Soc. Geol. Fr.*, 8, 533–540.
- Terrier, M., O. Serrano, and F. Hanot (2008), Reassessment of the structural framework of western Provence (France): Consequence on the regional seismotectonic model, *Geodin. Acta*, 21, 231–238, doi:10.3166/ga.21.231-238.
- Tesaro, M., M. K. Kaban, and S. A. P. L. Cloetingh (2008), EuCRUST-07: A new reference model for the European crust, *Geophys. Res. Lett.*, 35, L05313, doi:10.1029/2007GL032244.
- Tesaro, M., M. K. Kaban, and A. P. L. Cloetingh (2009), How rigid is Europe's lithosphere?, *Geophys. Res. Lett.*, 36, L16303, doi:10.1029/2009GL039229.
- Toutin-Morin, N., D. Bonijoly, C. Brocard, and M. Dubard (1993), Enregistrement sédimentaire de l'évolution post-hercynienne en bordure des Maures et du Tanneron, du Carbonifère supérieur à l'actuel, *Geol. Fr.*, 2, 3–22.
- Vacherat, A., F. Mouthereau, R. Pík, M. Bernet, C. Gautheron, E. Masini, L. Le Pourhiet, B. Tibari, and A. Lahfid (2014), Thermal imprint of rift-related processes in orogens as recorded in the Pyrenees, *Earth Planet. Sci. Lett.*, 408, 296–306.
- Vergés, J., and J. García-Senz (2001), Mesozoic evolution and Cainozoic inversion of the Pyrenean Rift, in *Peri-Tethys Memoir 6: Peri-Tethyan Rift/Wrench Basins and Passive Margins*, *Mém. Mus. Natl. Hist. Nat.*, vol. 186, edited by P. A. Ziegler et al., pp. 187–212, Paris.
- Vergés, J., H. Millán, J. A. Muñoz, M. Marzo, J. Cirès, T. Den Bezemer, R. Zoetemeijer, and S. Cloetingh (1995), Eastern Pyrenees and related foreland basins: Pre-, syn- and post-collisional crustal-scale cross-sections, *Mar. Petrol. Geol.*, 12(8), 893–915.
- Vially, R., and P. Trémolières (1996), Geodynamics of the Gulf of Lions: Implications for petroleum exploration, in *Structure and Prospects of Alpine Basins and Forelands*, *Peri-Tethys Mem.*, *Mém. Mus. Nat. Hist. Nat.* 170, vol. 2, edited by P. A. Ziegler and F. Horvath, pp. 129–158, Ed. du Mus., Paris.
- Villegier, M., and J. Andrieux (1987), Phases tectoniques post-éocènes et structuration polyphasée du panneau de couverture nord provençal (Alpes externes méridionales), *Bull. Soc. Géol. Fr.* III, 8(1), 147–156.
- Wallace, W. K. (2008), Yakataga fold-and-thrust belt: Structural geometry and tectonic implications of a small continental collision zone, in *Active Tectonics and Seismic Potential of Alaska*, edited by J. T. Freymueller et al., pp. 237–256, AGU, Washington, D. C., doi:10.1029/179GM13.
- Zarki-Jakni, B., P. van der Beek, G. Poupeau, M. Sosson, E. Labrin, P. Rossi, and J. Ferrandini (2004), Cenozoic denudation of Corsica in response to Ligurian and Tyrrhenian extension: Results from apatite fission track thermochronology, *Tectonics*, 23, TC1003, doi:10.1029/2003TC001535.
- Ziegler, P. A., J.-D. van Wees, and S. Cloetingh (1998), Mechanical controls on collision-related compressional intraplate deformation, *Tectonophysics*, 300, 103–129, doi:10.1016/S0040-1951(98)00236-4.