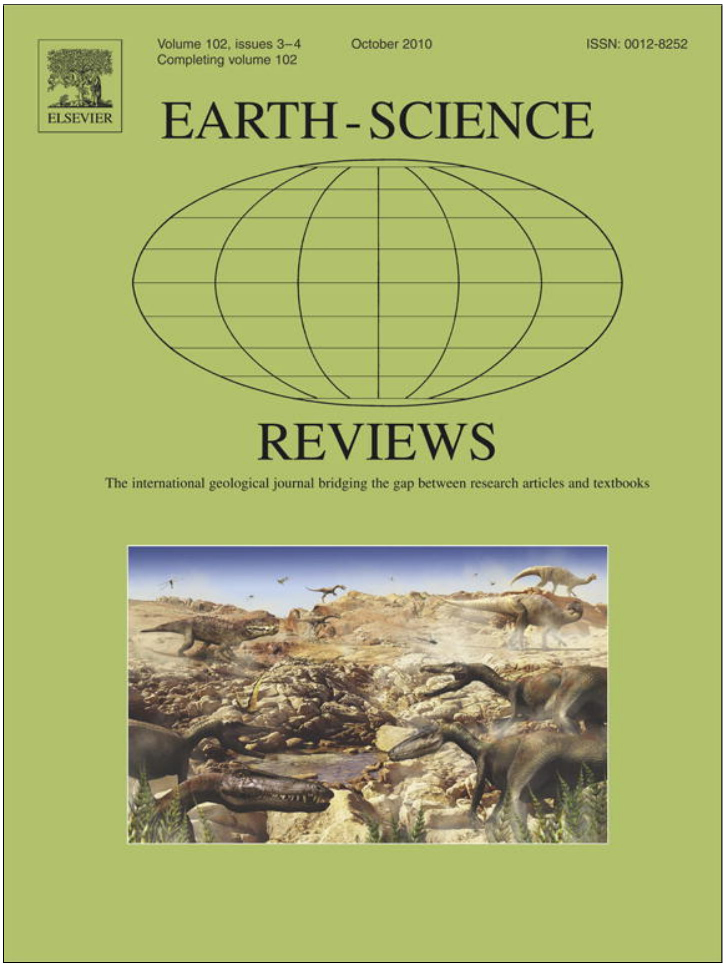
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Reconciling plate-tectonic reconstructions of Alpine Tethys with the geological–geophysical record of spreading and subduction in the Alps

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ABSTRACT

A new reconstruction of Alpine Tethys combines plate-kinematic modelling with a wealth of geological data and seismic tomography to shed light on its evolution, from sea-floor spreading through subduction to collision in the Alps. Unlike previous models, which relate the fate of Alpine Tethys solely to relative motions of Africa, Iberia and Europe during opening of the Atlantic, our reconstruction additionally invokes independent microplates whose motions are constrained primarily by the geological record. The motions of these microplates (Adria, Iberia, Alcapia, Alkapecia, and Tiszia) relative to both Africa and Europe during Late Cretaceous to Cenozoic time involved the subduction of remnant Tethyan basins during the following three stages that are characterized by contrasting plate motions and driving forces: (1) 131–84 Ma intra-oceanic subduction of the Ligurian part of Alpine Tethys attached to Iberia coincided with Eo-alpine orogenesis in the Alcapia microplate, north of Africa. These events were triggered primarily by foundering of the older (170–131 Ma) Neotethyan subduction slab along the NE margin of the composite African–Adriatic plate; subduction was linked by a sinistral transform system to E–W opening of the Valais part of Alpine Tethys; (2) 84–35 Ma subduction of primarily the Piemont and Valais parts of Alpine Tethys which were then attached to the European plate beneath the overriding African and later Adriatic plates. NW translation of Adria with respect to Africa was accommodated primarily by slow widening of the Ionian Sea; (3) 35 Ma–Recent rollback subduction of the Ligurian part of Alpine Tethys coincided with Western Alpine orogenesis and involved the formation of the Gibraltar and Calabrian arcs. Rapid subduction and arc formation were driven primarily by the pull of the gravitationally unstable, retreating Adriatic and African slabs during slow convergence of Africa and Europe. The upper European–Iberian plate stretched to accommodate this slab retreat in a very mobile fashion, while the continental core of the Adriatic microplate acted as a rigid indenter within the Alpine collisional zone. The subducted lithosphere in this reconstruction can be correlated with slab material imaged by seismic tomography beneath the Alps and Apennines, as well as beneath parts of the Pannonian Basin, the Adriatic Sea, the Ligurian Sea, and the Western Mediterranean. The predicted amount of subducted lithosphere exceeds the estimated volume of slab material residing at depth by some 10–30%, indicating that parts of slabs may be superposed within the mantle transition zone and/or that some of this subducted lithosphere became seismically transparent.

Contents

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1. The controversial fate of Alpine Tethys

Ever since Steinmann (1905) tried to relate the oceanic affinity of Alpine ophiolites to Alpine folding, a major challenge of Mediterranean geology has been to understand the fate of ocean basins preserved in the circum-Mediterranean mountain belts—how they formed, their size and, finally, how they were consumed. The ophiolitic sutures that mark these oceanic remains are imbricated with thrust sheets derived from the Early Mesozoic continental margins of the European and African plates, and of various microplates (Fig. 1). The lithospheric substratum of these oceanic relics has been subducted and appears today as positive P-wave anomalies, many at the base of the upper mantle (Figs. 2 and 3; e.g., Spakman et al., 1993; Wortel and Spakman, 2000; Piromallo and Morelli, 2003). Relating these anomalies at depth to the history of spreading, subduction and collision at the surface is crucial to understanding how mantle flow is coupled to the motion of tectonic microplates, whose arcuate boundaries and backarc basins betray extensive intraplate deformation (Fig. 1). This mobile tectonic style of the Alpine-Mediterranean realm challenges the simple notion of rigid plates.

The Alps outlined in Figs. 1 and 4 are a good place to take on this challenge, as they contain the remains of two Jurassic- to Cretaceous-age ocean basins, the Valais and Piemont–Liguria Oceans (Fig. 4) that together are referred to as Alpine Tethys (e.g., Stampfli et al., 1998; Schmid et al., 2004a). In Cenozoic time, former continental margins adjoining these basins were accreted to the upper plate of the Alpine Orogen represented today by the Austroalpine Nappes and Southern Alpine units (Fig. 4). This upper plate also contains relics of an older, Triassic ocean basin referred to generally as Neotethys (Fig. 1) or more specifically as the Meliata–Maliac Ocean and its adjacent distal continental margin, termed Hallstatt (Fig. 4).

A controversy arose, waged to the present day, regarding the timing and amount of crustal subduction in the Alps. At the time of Steinmann's pioneer work, Ampferer (1906) proposed subduction of basement rock ("Verschluckung" or "swallowing") to account for the discrepancy in the Alps between the restored area of imbricated and folded Mesozoic sedimentary rocks and the available basement substratum for this cover. Early plate-tectonic reconstructions re-addressed this fundamental problem (Laubscher, 1970, 1975), primarily by considering subduction with respect to the relative motion of just two plates (Africa and Europe, e.g., Channell and Horvath, 1976), three plates (Adria, Africa and Europe; Biju-Duval et al., 1977; Dercourt et al., 1986), or a wealth of smaller microplates (Dewey et al., 1973). However, they lacked crucial information on the size of Alpine Tethys and the precise age of its demise. The gap in knowledge between plate-motion studies and field-based tectonic syntheses was large, primarily because modern structural petrology and geochronology were in their infancy and also because geologists were preoccupied with understanding collisional structures, which in most areas overprint structures related to the spreading and subsequent subduction of oceanic lithosphere.

Far from abating, controversy on the fate of Alpine Tethys has been fuelled by recent geological and geophysical research. On the one hand, simplistic plate-motion reconstructions suggest the creation of 650–1100 km of oceanic lithosphere within Alpine Tethys in an E–W direction, i.e., perpendicular to the former spreading axis, and some 1500 km in a N–S direction (models reviewed in Capitanio and Goes, 2006, their Fig. 3a). These amounts deduced from the motion of Africa with respect to Europe in Early Jurassic to Early Cretaceous time would call for post-Early Cretaceous (<135 Ma) subduction of an equal amount of oceanic lithosphere. On the other hand, only about 200 km (Dewey et al., 1989) to 350 km (Savostin et al., 1986) of pre-collisional, north–south convergence between Africa and Europe are indicated by plate-motion studies for Paleocene to Eocene time. Some 350 km of convergence are obtained for the same time interval from modern palinspastic reconstructions based on surface geology and subsurface geophysical data in the Central Alps (Schmid et al., 1996, 1997), but such reconstructions tend to neglect a potentially much larger amount of shortening related to oceanic subduction. Plate-motion estimates of N–S convergence between Africa and Europe increase to a total of between 400 km (Savostin et al., 1986; see Fig. 3a in Capitanio and Goes, 2006) and 950 km (Dewey et al., 1989, their Fig. 1a) after inclusion of the Late Cretaceous motion of Africa (84–67 Ma and 92–65 Ma, respectively). However, there still remain some 550 to 1100 km of N–S plate convergence between Africa and Europe that are unaccounted for if one accepts the 1500 km estimate for the N–S length of Alpine Tethys to be correct. Either the N–S length of Alpine Tethys was smaller than deduced from plate-motion studies and palinspastic reconstructions, and/or the Adriatic microplate moved independently (Dercourt et al., 1986) of the African plate for at least part of the period considered above. We emphasize that independent motion of the Adriatic microplate would allow for a more substantial component of east–west-directed subduction of oceanic lithosphere than predicted from Africa–Europe plate convergence. This subduction must have affected Alpine Tethys or older parts of Tethys (Neotethys) further to the east.

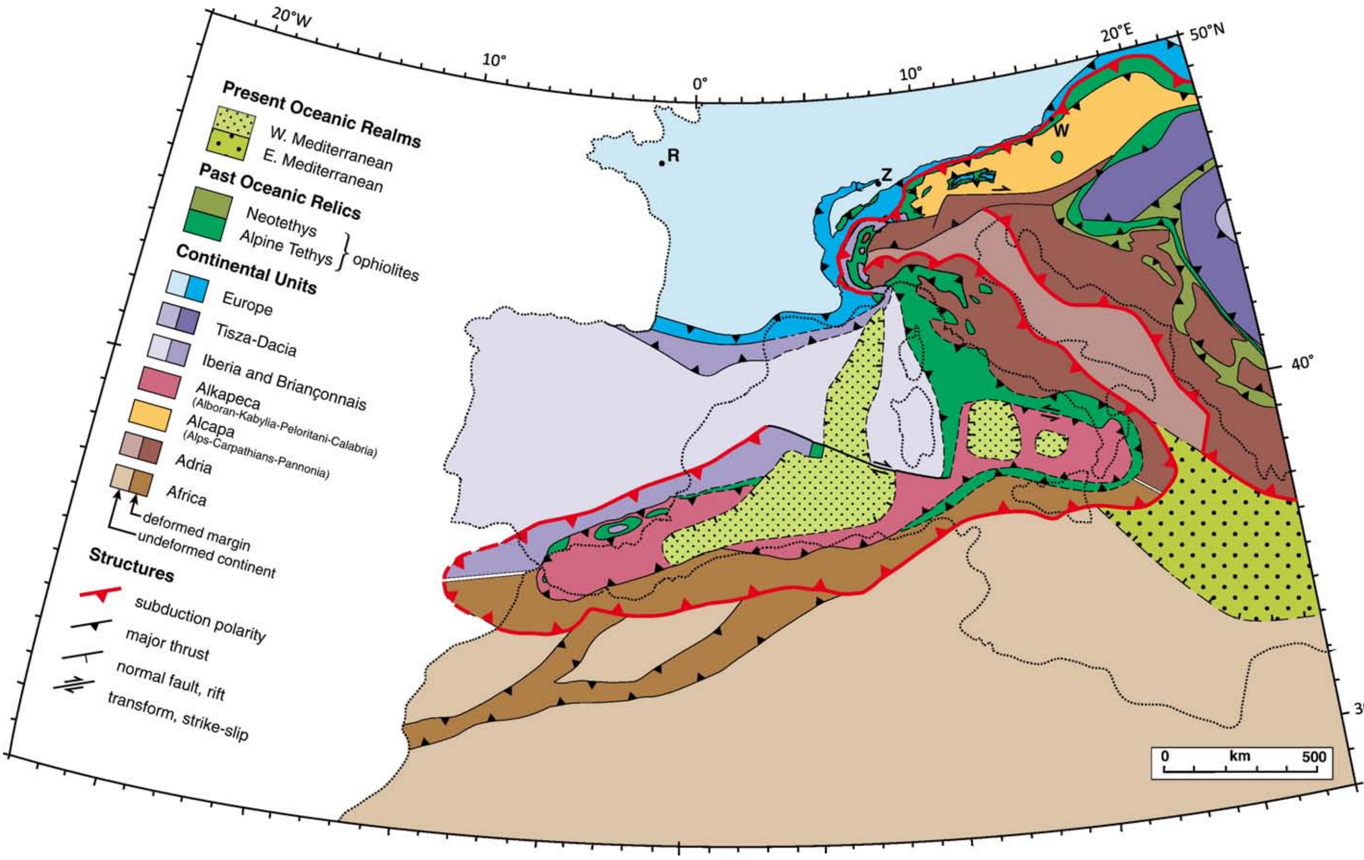


Fig. 1. Tectonic map of Mesozoic–Cenozoic mountain belts and ocean basins in the Alpine–Western Mediterranean area. The tectonic units in this map are plates or fragments of plates that have moved independently since Jurassic time and were amalgamated in Cenozoic–Recent time. Subduction polarities shown in red are determined from the dip of subducted lithospheric slabs imaged by seismic tomography (see Fig. 3). Note that some of these subduction polarities pertain to ancient plate boundaries (e.g. parts of the Alps), while others relate to boundaries that are still active (e.g. External Dinarides, Southern Apennines, Calabria, Betic–Rif). References: Alps, Dinarides, Carpathians (Schmid et al., 2004a, 2008); Italy (Bigi et al., 1989), Betic Cordillera, Alboran block, Northern Africa (Frizon de Lamotte et al., 2000; Michard et al., 2006); Western Mediterranean Sea (Roca et al., 2004); Ionian Sea (Chamot-Rooke et al., 2005).

The advent of travel-time seismic tomography (e.g., Spakman et al., 1993; Wortel and Spakman, 2000) may help resolve such issues, as it allows us for the first time to image subducted slabs residing in the transitional zone between upper and lower mantle beneath the Alpine mountain chains (Figs. 2 and 3). In fact, the positive P-wave velocity anomaly at 500–650 km depth that extends SW from the Alps to the northern central part of the Italian peninsula (blue anomalous area beneath the northern Adriatic Sea in Fig. 2, blue anomalous area to the right of A in Fig. 3b, c) is a viable candidate for this subducted lithosphere because it lies between, and is therefore older than, the E- and W-dipping subduction slabs beneath the Dinarides and Apennines, respectively. Correlating such anomalies with the motion history of the overlying plates is an important by-product of the kinematic reconstructions presented in this paper and helps us to infer the forces driving subduction.

A second controversy pertains to striking differences in tectonic style between the Eastern and Western Alps, and the possible relationship of these differences to the age and direction of past plate motions in the Tethyan domain. Whereas plate-motion reconstructions involving only Africa, Iberia and Europe predict that Alpine Tethys was still spreading as the African plate moved ENE to NE relative to Europe between 130 and 80 Ma (300–400 km in Capitanio and Goes, 2006 and references therein), geological studies in the Eastern Alps indicate the subduction of dominantly continental lithosphere. This led to the formation of a Late Cretaceous (110–90 Ma, Eo-alpine) eclogite-facies metamorphic belt (purple areas in Fig. 5; e.g., Schuster, 2003; Schmid et al., 2004a; Thöni, 2006) with stretching lineations indicating NW- to W-directed nappe stacking and exhumation (blue arrows in Fig. 5). This contrasts with the Western Alps, which show a substantially younger (Cenozoic) high-pressure metamorphism and top-N to -NW nappe transport associated with S- to SE-directed subduction of Alpine Tethys (green arrows in Fig. 5). The Cenozoic subduction in the Western Alps propagated from SE to NW, as documented by progressively younger ages of flysch and high-pressure metamorphism going from originally internal to external units (e.g., Dal Piaz et al., 1972; Ernst, 1973; Froitzheim et al., 1996; Schmid et al., 1996, 1997; Stampfli et al., 1998). This led Froitzheim et al. (1994) to propose that the Alps actually comprise two orogens: An older Late Cretaceous or Eo-alpine orogen in the Eastern Alps (Austroalpine units) that forms the upper plate of a younger, Cenozoic orogen in the Western Alps (Fig. 5). During Cenozoic collision in the Western Alps and Apennines, the remnants of the two basins of Alpine Tethys and large upper crustal slivers of the European lower plate were accreted to the by-then rigid upper plate. Prior to Cenozoic collision, these two oceanic basins had opened and closed at different times in Jurassic to Eocene time (e.g., reviews in Stampfli et al., 1998; Schmid et al., 2004b). Understanding these differences in tectonic style and basin history in light of plate motions and the geologic record is crucial to resolve the controversies outlined above.

This paper demonstrates that the subduction of Alpine Tethys in Late Cretaceous to Paleogene time involved plate-boundary reorganizations among as many as seven plates, including the very mobile Adriatic microplate. These reorganizations ultimately led to the rise of the Alps and other circum-Mediterranean mountain belts, even up to the present time. The second and third chapters of this paper present

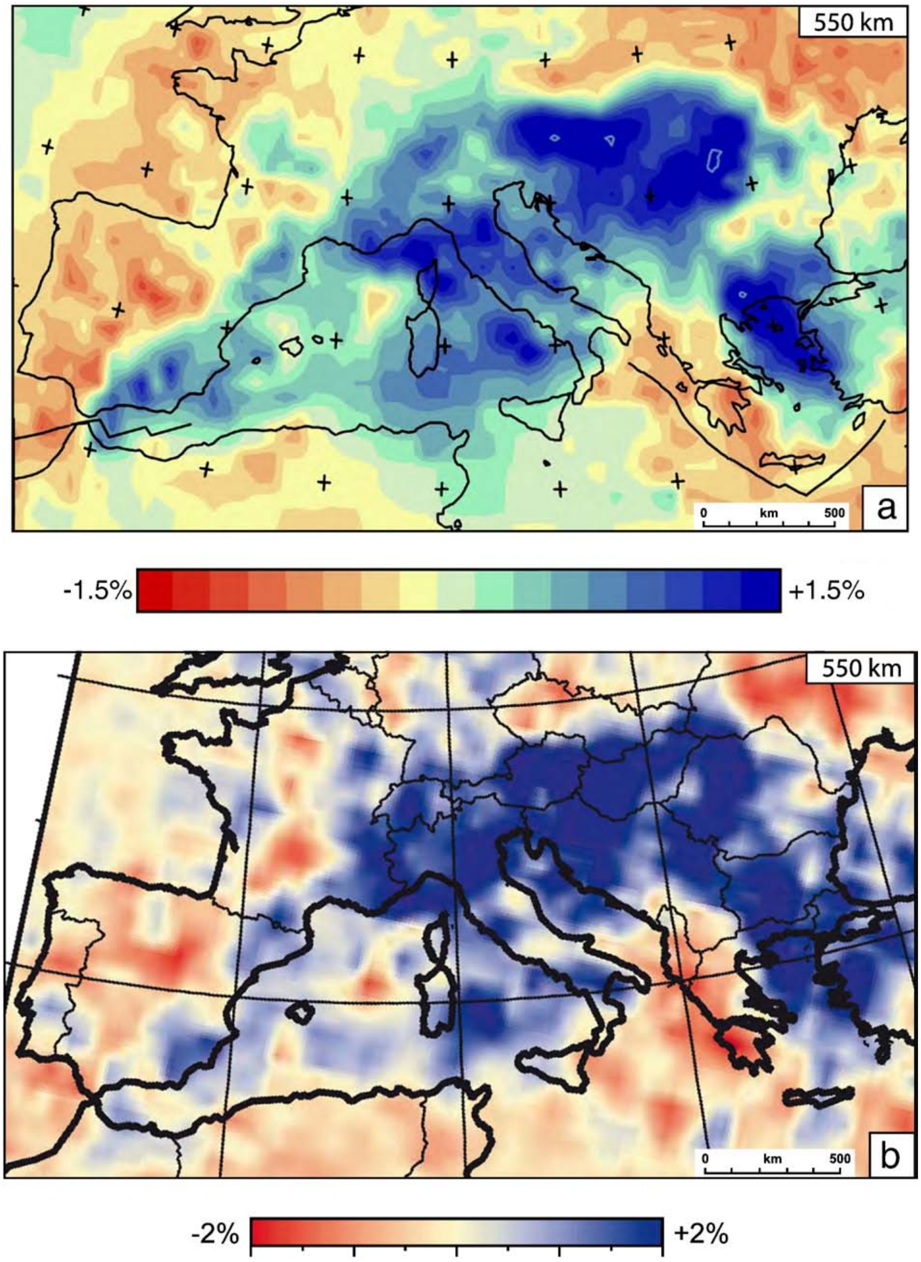


Fig. 2. Seismic tomographic maps of the upper mantle beneath Europe and the Mediterranean region: (a) horizontal slice at depth of 550 km with coastal outlines (courtesy of W. Spakman); (b) horizontal slice at 550 km with coastal outlines and national boundaries (Piromallo and Morelli, 2003, modified from their Fig. 8). Positive P-wave velocity anomalies (blue) and their relationship to Mesozoic provenance and subduction history are discussed in Sections 5 and 6.

the nomenclature, rationale and methods used to construct a new plate-tectonic model for Alpine Tethys that incorporates evidence for intermittently independent motions of the Adriatic microplate in Late Cretaceous and Cenozoic time. The fourth chapter then reviews the geologic evidence for a series of plate-tectonic maps and cross sections spanning the period from the end of Mesozoic sea-floor spreading to Cenozoic Alpine collision. We propose that the subduction of Alpine Tethys was conditioned by Mesozoic east–west transform faulting and Eo-alpine orogenesis, itself possibly triggered by subduction of a western embayment of the northern branch of Neotethys. The new plate-tectonic model further enables us to quantify the rates and amounts of convergence among plates, and in chapter five, to correlate their motion with the entrainment of lithosphere in hanging slabs and slab graveyards at the base of the transition zone in the mantle. Almost half of this subducted lithosphere is estimated to be continental, fuelling speculation in the sixth chapter that the negative buoyancy of both old oceanic and subcontinental lithospheres was a dominant force driving subduction of Alpine Tethys prior to collision in the Alps. Since the onset of this collision some 35 Ma, Adria's counter-clockwise rotation has been driven by northward push from Africa, while slab pull has effected rapid rollback subduction of the remaining parts of Alpine Tethys and opening of the Western Mediterranean ocean basins. We conclude in the seventh chapter by assessing our notions on the subduction of Alpine Tethys in the context of previous concepts, from cylindrism in the Alps to the single- and double subduction models of today.

2. Nomenclature of oceans and tectonic units in the Alps and adjacent mountain belts

Tethys is the name originally given to the Mesozoic oceanic domain preserved in the Alpine mountain belts (Suess, 1888), "the great

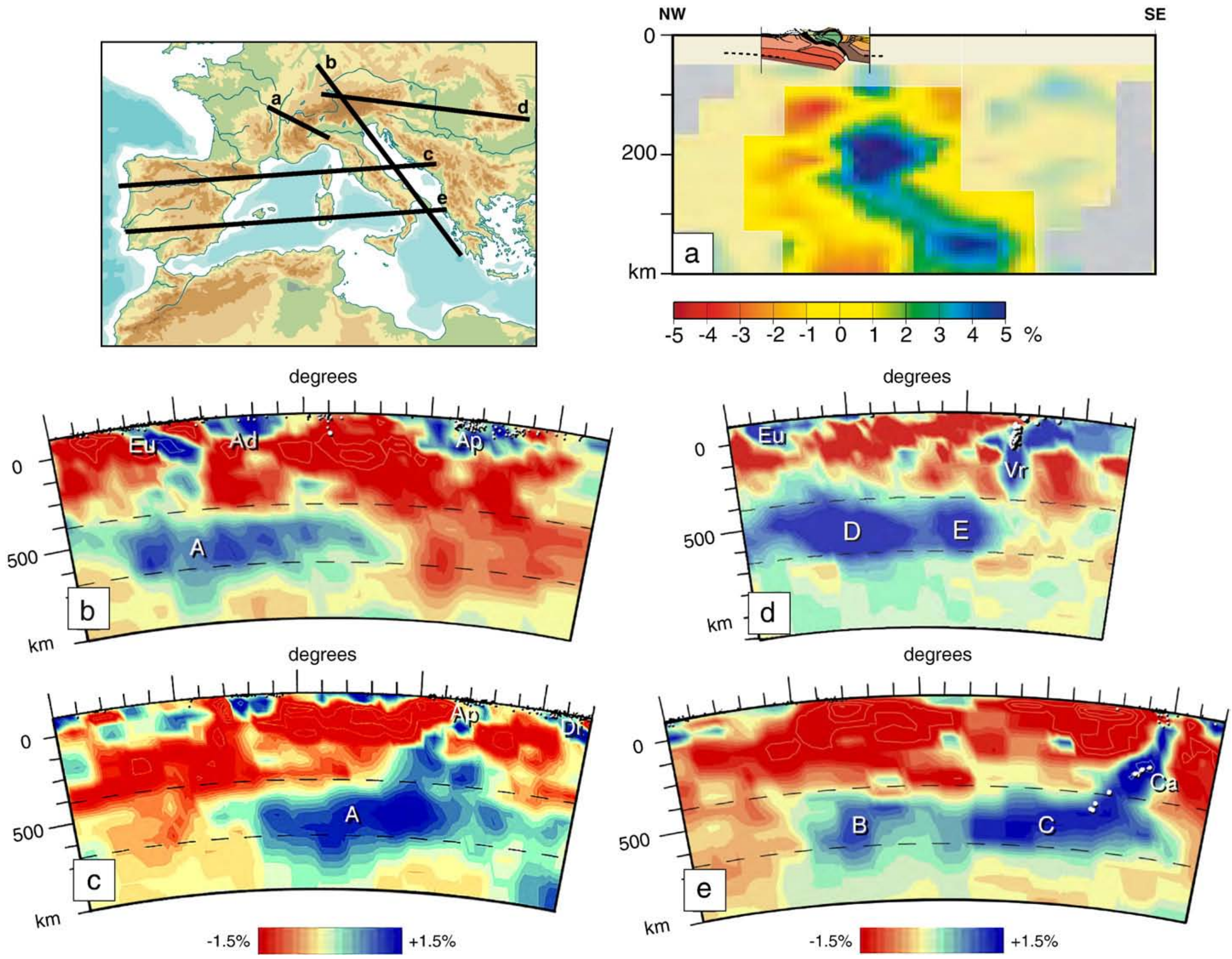
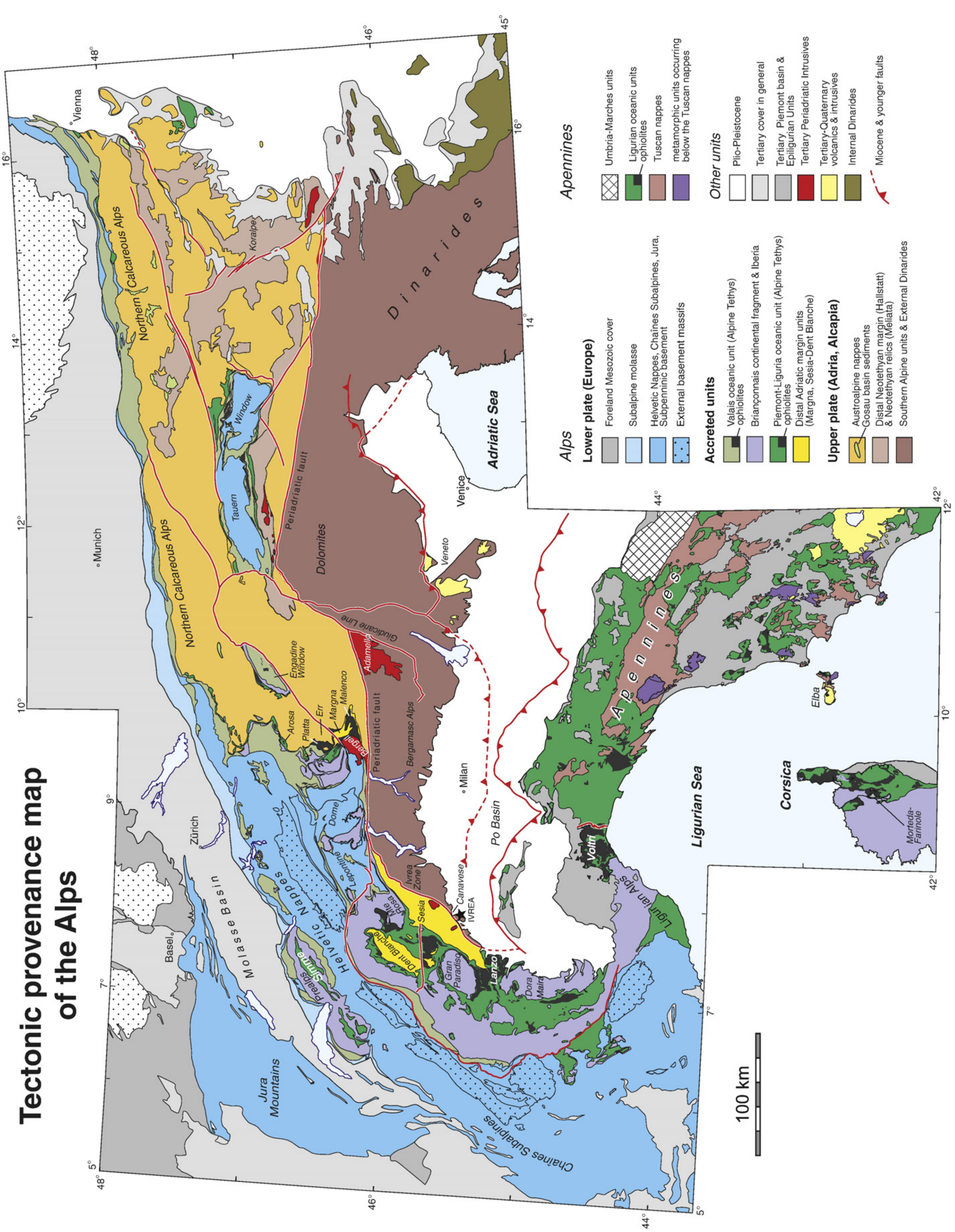


Fig. 3. Seismic tomographic sections along transects of Bijwaard and Spakman (2000) and modified from Spakman and Wortel (2004) showing relationship of lithospheric slabs resting at the base of the transitional zone to location of Cenozoic to Recent mountain belts and arc–trench systems: (a) NW–SE section parallel to the ECORS-CROP transect across the Western Alps shown in inset at top, modified from Fig. 13a in Kissling et al. (2006); (b) NW–SE transect from the Eastern Alps through the Adriatic Sea and Southern Apennines, modified from Fig. 2.A2.3, Profile j of Spakman and Wortel (2004); (c) NE–SW transect from Dinarides across the N. Apennines and Corsica to N. Spain; modified from Fig. 2.A2.2, Profile o of Spakman and Wortel (2004); (d) ESE–WNW transect from the S. Carpathians (Vrancea) to the Eastern Alps modified from Fig. 2G of Wortel and Spakman (2000); (e) E–W transect from Calabria through Corsica and the Balearic islands to S. Spain; Fig. 2.A2.2, Profile i of Spakman and Wortel (2004). Positive P-wave anomalies in the mantle transition zone at 450–650 km depth (labelled A–E) are interpreted to be part of a single, large anomaly that represents the subducted remnant of Alpine Tethys and its adjacent continental lithosphere (see Figs. 2 and 17 and Section 5). For convenience, this anomaly is divided into smaller subanomalies: A = Western Alpine–Ligurian anomaly, B = Alboran anomaly, C = Calabrian–Southern Apennine anomaly, D = Eastern Alpine anomaly, E = Pannonian anomaly. Symbols for shallow positive anomalies at <300 km depth: Ad = Adriatic indenter, Ap = Apenninic slab, Ca = Calabrian slab, Di = Dinaric slab, Eu = Miocene–Recent European slab beneath Alps, Vr = Vrancea slab.

ocean which once stretched across Eurasia" and whose "folded and crumpled deposits stand forth to heaven in Thibet, Himalaya and the Alps" (Suess, 1893, p. 183). Following Stampfli and Borel (2002), we adopt the more specific term *Alpine Tethys* for two Jurassic–Cretaceous ocean basins in the Alps (*Valais* and *Piemont–Liguria*, Fig. 4) whose opening was kinematically linked to the opening of the Atlantic Ocean. The term *Neotethys* denotes late Paleozoic–Mesozoic oceanic domains whose opening was related to spreading behind continental fragments that broke off Pangea (Sengör, 1979; Stampfli and Borel, 2002). Here, we distinguish two main branches of Neotethys that were originally located to the east and south of the present Alps: (1) a southern branch, part of which still exists in the Ionian part of the Eastern Mediterranean Sea (Fig. 1). We will refer to it simply as the *Ionian Sea*, but note that some (mostly French) colleagues have adopted the term *Mesogea* (Biju-Duval et al., 1977) despite the fact that this was originally used as a synonym for Suess' entire Tethys (e.g., Haug, 1908–1911). The age of this southern, Ionian branch of Neotethys is still unknown, but based on indirect arguments is thought to be of Cretaceous age by some (Dercourt et al., 1986; Catalano et al., 2001; Chamot-Rooke et al., 2005; Schmid et al., 2008) or as old as Triassic or Permian age by others (Stampfli and Borel, 2004); (2) a northern branch of Neotethys which we refer to as *Meliata–Maliac–Vardar*. This branch started to open in Triassic time and had an arm (Meliata Ocean and adjacent Hallstatt distal passive margin) that extended into both the Eastern Alps (Neotethys in Figs. 1 and 4; e.g., Schmid et al., 2004a) and the Western Carpathians (e.g., Mandl and Ondrejicka, 1991, 1993). However, its main part (*Maliac–Vardar*; e.g., Schmid et al., 2008) is preserved as ophiolites in the Dinarides (Pamić, 2002; Tomljenovic, 2002; Tomljenovic et al., 2008) and Hellenides (Ferrière, 1982), as shown in Fig. 1. The evolution of these two branches of Neotethys is linked to that of Alpine Tethys in a manner that is still largely unknown.

In adopting the term Alpine Tethys, we purposefully avoid *Pennine* or *Penninic*, both classical expressions for Cenozoic nappes in the Alps


Tectonic provenance map
of the Alps
Alps
Lower plate (Europe)
Foreland Mesozoic cover
Subalpine molasse
Helvetic Nappes, Chaînes Subalpines, Jura, Subpenninic basement
External basement massifs
Accreted units
Valais oceanic unit (Alpine Tethys) ophiolites
Briançonnais continental fragment & Iberia
Piemont-Liguria oceanic unit (Alpine Tethys) ophiolites
Distal Adriatic margin units (Margna, Sesia-Dent Blanche)
Upper plate (Adria, Alcapia)
Austroalpine nappes
Gosau basin sediments
Distal Neotethyan margin (Hallstatt) & Neotethyan relics (Meliata)
Southern Alpine units & External Dinarides
Apennines
Umbria-Marches units
Ligurian oceanic units ophiolites
Tuscan nappes
metamorphic units occurring below the Tuscan nappes
Other units
Plio-Pleistocene
Tertiary cover in general
Tertiary Piemont basin & Epiligurian Units
Tertiary Periadriatic Intrusives
Tertiary-Quaternary volcanics & intrusives
Internal Dinarides
Miocene & younger faults
100 km
Vienna
Munich
Zürich
Basel
Milan
Venice
Northern Calcareous Alps
Koralpe
Tauern Window
Engadine Window
Periadriatic fault
Giudicarie Line
Adamello
Bergell
Bergamasc Alps
Dolomites
Dinarides
Veneto
Adriatic Sea
Po Basin
Apennines
Elba
Corsica
Mortola-Farinole
Ligurian Sea
Ligurian Alps
Voltri
Lanzo
Dora Maira
Gran Paradiso
Dent Blanche
Sesia
Monte Rosa
Ivrea Zone
Canavese
IVREA
Lepontine
Dome
Arosa
Platta
Err
Margna
Malenco
Helvetic Nappes
Molasse Basin
Jura Mountains
Chaînes Subalpines
Simme
Prealps

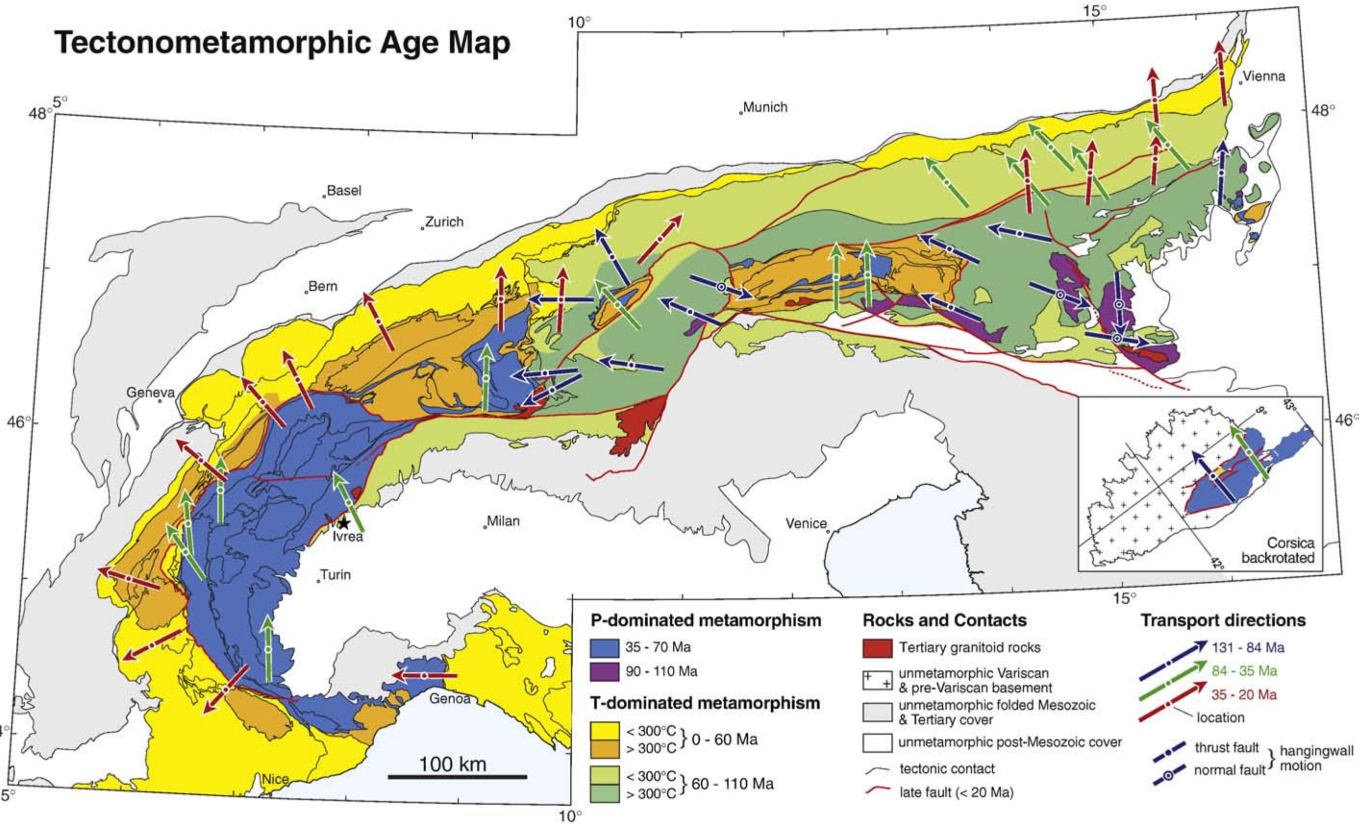


Fig. 5. Age of metamorphism and kinematics in the Alps and Corsica. Corsica is depicted in its pre-late Oligocene back-rotated orientation. Distribution of metamorphic ages is modified from inset map of Oberhänsli et al. (2004) as described in Handy and Oberhänsli (2004). Pressure-dominated metamorphism (blue and purple areas) includes blueschist-, eclogite- and HP greenschist-facies assemblages as well as UHP minerals (e.g., coesite); Temperature-dominated metamorphism includes assemblages ranging from sub-greenschist- (yellow, light green) to greenschist- and amphibolite-facies (orange, dark green). Arrows indicate transport direction taken from the following sources: Corsica (Malavieille et al., 1998; Molli, 2008); Ligurian Alps (Vignaroli et al., 2008), Western Alps (Malavieille et al., 1984; Choukroune et al., 1986; Vuichard, 1989; Philippot, 1990; Fügenschuh et al., 1999; Loprieno, 2001; Ceriani and Schmid, 2004); Central Alps (Babist et al., 2006; Pleuger et al., 2008; Nagel, 2008), Lower Austroalpine and adjacent Piemont–Liguria units of E. Switzerland (Ring et al., 1989; Liniger and Nievergelt, 1990; Handy, 1996); Engadin Window (Ring et al., 1989; Bousquet et al., 2002); Eclogite Zone in the Tauern Window (Kurz et al., 2008); Northern Calcareous Alps (Eisbacher and Brandner, 1996; Peresson and Decker, 1997), Austroalpine basement units including eclogite-bearing rocks of the Koralpe-Wölz unit (Ratschbacher et al., 1989; Froitzheim et al., 2008) and Radstadt Tauern (Becker, 1993).

derived from the Mesozoic realm that was only partly underlain by oceanic crust (North Penninic = Valais, South Penninic = Piemont–Liguria) and incorporated massive volumes of continental (Subpenninic = distal European margin; Middle Penninic = Briançonnais) crust. Although still used by Alpine geologists as a convenient field term for nappes forming the core of the present Alpine orogen, *Penninic* and its northern, middle and southern subdivisions implicitly reflect the dated notion that the present, top-to-bottom order of Alpine nappes stacked in Cenozoic time mirror the Mesozoic paleogeography from south to north as inherited during N- to NW-directed cylindrical folding and thrusting (e.g., Argand, 1911). This is misleading. Long since the concepts of cylindrism and nappism became established in the first half of the 20th century, numerous studies have demonstrated that significant east–west transform motion sub-parallel to the Alpine belt preceded nappe stacking (Laubscher, 1975; Trümpy, 1976; Kelts, 1981; Weissert and Bernoulli, 1985; Schmid et al., 1990). Moreover, Cenozoic nappe stacking involved extensional exhumation in addition to thrusting in the sense of classical nappe tectonics (e.g., Schmid et al., 1996; Escher and Beaumont, 1997). We therefore emphasize that the tectonic plates delineated in this paper do not necessarily correspond to continental and oceanic domains in classical Alpine paleogeography (e.g., Trümpy, 1980). As shown below, plate boundaries shifted repeatedly from within ocean basins to ocean–continent margins during Jurassic to Eocene time.

It follows that the term *Adria* or *Adriatic* as used in this paper denotes a microplate with both continental and oceanic parts between the European plate to the north, the Iberian microplate to the west, and the African plate to the south (Doglioni and Flores, 1997; Stampfli and Borel, 2002). This definition differs from that in reconstructions where the Adriatic microplate is equated solely with continental lithosphere (e.g., Apulian plate of Schmid et al., 2004a). From Late Cretaceous to Early Cenozoic time, possibly earlier, the northern part of the continental margin of Adria separated to become the Alcapia microplate. The plate name *Alcapia* derives from the acronym ALCAPA (Alps-Carpathians-Pannonian Basin) for the far-travelled nappes that today make up the Austroalpine units of the Eastern Alps and Western Carpathians (Fig. 1) and include remnants of the northwestern end of the Meliata–Maliac Ocean (Schmid et al., 2004a, 2008). Thus, we use Adria to refer only to the partly

Fig. 4. Tectonic provenance map of the Alps. Continental units in this map are the relics of deformed margins that formed parts of tectonic plates depicted with corresponding colors in Figs. 8–15. Tethyan oceanic units (Valais, Piemont–Liguria, and Meliata) changed their plate affinity often and therefore have distinct colors to distinguish them from continental units. Map modified from Froitzheim et al. (1996) and Schmid et al. (2004a). Projection taken from Sheets 1 and 2 of the Structural Model of Italy (Bigi et al., 1989).

undeformed microplate located south of the present-day Periadriatic fault system ("Adriatic and Apulian plates sensu stricto" of Stampfli et al., 1998; see also Michard et al., 2002), as depicted in Figs. 1 and 4. Argand (1924) and later Channell and Horvath (1976) and Channell et al. (1979) considered the Adriatic microplate to have been a promontory of the African plate, whereas most workers since Biju-Duval et al. (1977) assume that it separated from Africa sometime between Permian and Late Cretaceous times. In this paper, we highlight the intermittently independent evolution of the Adriatic microplate and show why parts of it remained coherent throughout the subduction of Alpine Tethys. In this context, it is important to distinguish the Adriatic microplate from the *Adriatic indenter*, which in Oligo-Miocene time formed a rigid block bounded to the north and west by the Periadriatic fault system in the Alps (Fig. 4). The fragmentation and indentation of this block into the accreted crustal units of the Alpine orogenic wedge contributed to oroclinal bending of the Western Alps (Schmid et al., 1989; Collombet et al., 2002) and eastward lateral extrusion of crustal wedges in the Eastern Alps (e.g., Ratschbacher et al., 1991).

Finally, the units of the Alps–Apennines chain referred to as *Briançonnais* and *Alkapeca* (Fig. 1) were originally narrow fragments of continental lithosphere that rifted from the European continental margin in Jurassic time. *Alkapeca* is an acronym (Alboran–Kabylia–Peloritani–Calabria fragment, Boullin et al., 1986; Michard et al., 2002, 2006) which denotes the present locations in the southern and western Mediterranean area of far-travelled blocks and thrust sheets that acquired their present positions during Miocene-to-Recent retreat in the hangingwalls of the Gibraltar and Calabrian rollback subduction systems (Fig. 1). These continentally derived nappes presently overlie ophiolitic units derived from the Ligurian part of Alpine Tethys. For the purposes of our plate reconstructions, we distinguish Alkapeca from *Alkapecia*, the name given to the short-lived Jurassic–Early Cretaceous microplate that comprised both the Alkapeca continental fragment and adjacent Liguria oceanic lithosphere. Similarly, *Tiszia* is our designation for a microplate that separated from Europe in Middle Jurassic time (Haas and Pero, 2004) and subsequently acquired an Adriatic affinity. Its continental core (Tisza or Tisza Mega-Unit, Schmid et al., 2008) was sutured to the Adriatic microplate when the Dinarides formed in Late Cretaceous time, then was re-united with Europe during Miocene formation of the Carpathians (e.g., Ustaszewski et al., 2009). Today, the amalgamated Tisza and Dacia units (Tisza–Dacia in Fig. 1) and parts of ALCAPA form the basement substratum of the Pannonian Basin inside the arc of the Carpathian mountains (see Schmid et al., 2008 for a review). The Tisza–Dacia unit plays only a marginal role in our reconstruction presented below.

3. Reconstructing the plate tectonics of Alpine Tethys – Approach and limitations

3.1. Timing of pre-collisional events in the Alps

The starting point for the plate-tectonic reconstruction presented below is the timetable of pre-collisional events in the Alps shown in Fig. 6. This figure summarizes stratigraphic, petrological and geochronological information used to constrain the timing of plate-boundary activity in and around Alpine Tethys. The horizontal axis of Fig. 6 shows the Jurassic–Cretaceous paleogeographic domains in a NW–SE oriented section across the Alps and is based on palinspastic reconstructions obtained by retrodeforming the Cretaceous and Cenozoic nappe stacks in the Eastern and Western Alps (see references in caption to Fig. 6). The directions of thrusting and trench migration indicated in this figure were obtained from transport directions of Alpine tectonic units during Late Cretaceous to Cenozoic time depicted in Fig. 5.

Details of Fig. 6 are discussed in the context of the maps and sections in the next section, but some salient features of this timetable are summarized here in order to make the plate-motion paths in the next section better understandable: East–west opening of the Piemont–Liguria Ocean basin began with rifting (200–170 Ma) and culminated with extensional exhumation of subcontinental mantle and sea-floor spreading (170–131 Ma). This opening was broadly coeval with intra-oceanic subduction in the Meliata–Maliac–Vardar ocean basin (Stampfli et al., 1998; Schmid et al., 2008) followed by the obduction of the western part of the Jurassic-age Vardar oceanic lithosphere onto the eastern continental margins of Alcapia and Adria (Schmid et al., 2008). Oblique opening of the Valais ocean basin from 131 to 93 Ma was linked both to the opening of the Bay of Biscay and to intracontinental subduction and nappe stacking in the Eastern Alps, referred to as the Eo-alpine Orogeny (e.g., Faupl and Wagreich, 2000).

Closure of Alpine Tethys occurred in three stages, the first two of which are recorded in the Alps: A first stage (131–118 Ma) involved east-directed intra-oceanic subduction of part of the Ligurian ocean basin and overlapped in time with Eo-alpine orogenesis (131–84 Ma). A second stage (84–35 Ma) entailed southeast-directed subduction, initially of the Piemont Ocean and the western part of the Ligurian Ocean, and finally of the Valais Ocean and the distal European continental margin. The third and final stage (35 Ma–Recent) involved collision in the Alps and rollback subduction of most of the remaining eastern Ligurian Ocean. This final stage is preserved in nappes of the Apennines, Calabria, Betic Cordillera, Rif and Maghrebides.

We note that the first two stages of this subduction history differ from some recent models (e.g., Piromallo and Faccenna, 2004) in which subduction of Alpine Tethys is considered to be a product of continuous northwest–southeast convergence between Adria and Europe throughout Late Cretaceous and Paleogene time. Below, we show how this subduction began earlier and was punctuated by a radical change in the motion path for Adria at about 84 Ma associated with plate reorganization in Late Cretaceous time.

3.2. Plate motion paths—boundary conditions and assumptions

Fig. 7 shows the motion paths of five reference points (a–e) attached to three of the principle plates involved in the history of Alpine Tethys: Iberia (a, b), Africa (c, d) and Adria (e). These points are all situated on crust that was largely unaffected by Cenozoic deformation. Their motion paths are shown with respect to stable Europe. For the sake of simplicity and because of the uncertainties in our approach, all motions are two-dimensional, i.e., within the plane of projection of the Earth's surface onto the map of Fig. 7. The times for fixing the location of points a–e in Fig. 7 (170, 131, 118, 94, 84, 67 and 35 Ma) are key moments in the geological record of Alpine Tethys, and (except for 94 Ma) also correspond to well-defined ocean-floor magnetic anomalies in the Central and Northern Atlantic. Also, these times are identical to those used by Capitanio and Goes (2006) in their review of plate-kinematic reconstructions for Alpine Tethys. The newest time scale of Gradstein et al. (2004) is used to translate stratigraphic age into absolute time. This scale generally yields younger ages for epochs and stages than those previously used in the Alpine literature (e.g., Harland et al., 1989).

Points a, b, c and d follow paths in the plate-kinematic analysis of Savostin et al. (1986) based on magnetic anomalies in the Central and Northern Atlantic (Westphal et al., 1986). Their study was chosen as the best for the overall motion of Africa and Iberia because it prescribes a largely transform motion of Iberia with respect to Europe in Cretaceous time. Other reconstructions predict oblique-sinistral opening of a basin floored by oceanic crust that was up to 200 km wide in the present-day Pyrenees (e.g., Royer et al., 1992; Rosenbaum et al., 2002a). In fact, there is considerable debate on the nature of the pre-Pyrenean lithosphere and that of the Valais branch of Alpine

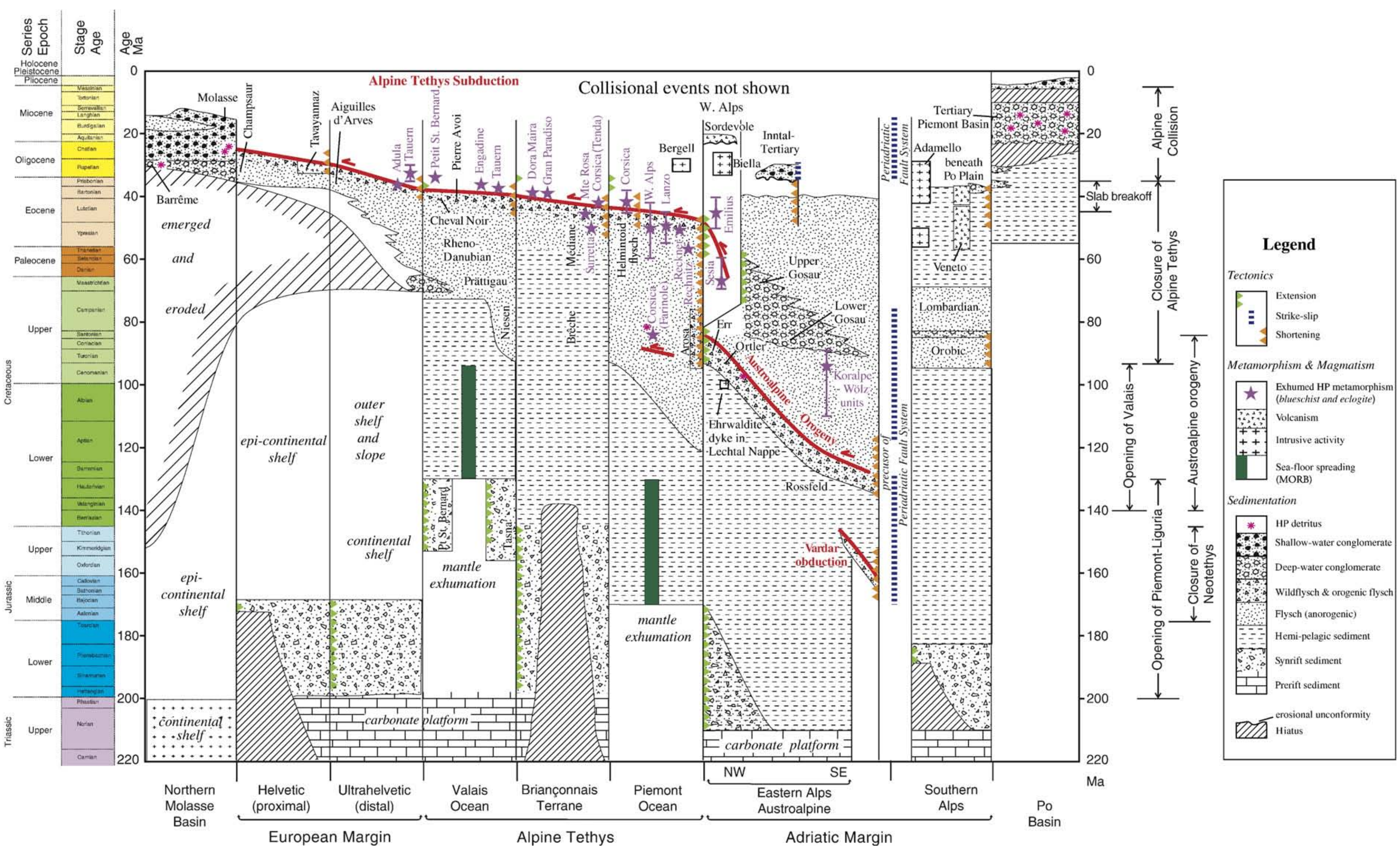


Fig. 6. Timetable of geologic events related to subduction in the northern part of Alpine Tethys. Horizontal border is aligned roughly along a NW–SE transect of Alpine Tethys and its continental margins. Time scale according to Gradstein et al. (2004). Figure incorporates information from sources cited in text and from reviews of Trümpy (1980, Fig. 41), Schmid et al. (1996, Fig. 4), Schmid et al. (1997, Fig. 14-20), Escher and Beaumont (1997, Fig. 16-8), Stampfli et al. (1998, Fig. 4), Manatschal and Müntener (2009, Fig. 6). Age of HP and UHP metamorphism taken from reviews of Berger and Bousquet (2008), Handy and Oberhänsli (2004) and Desmons et al. (1999), as well as from Amato et al. (1999), Rubatto et al. (1998), Rubatto and Hermann (2003), Liati et al. (2003a,b), Lapen et al. (2003), Mahlen et al. (2005), and Federico et al. (2007).

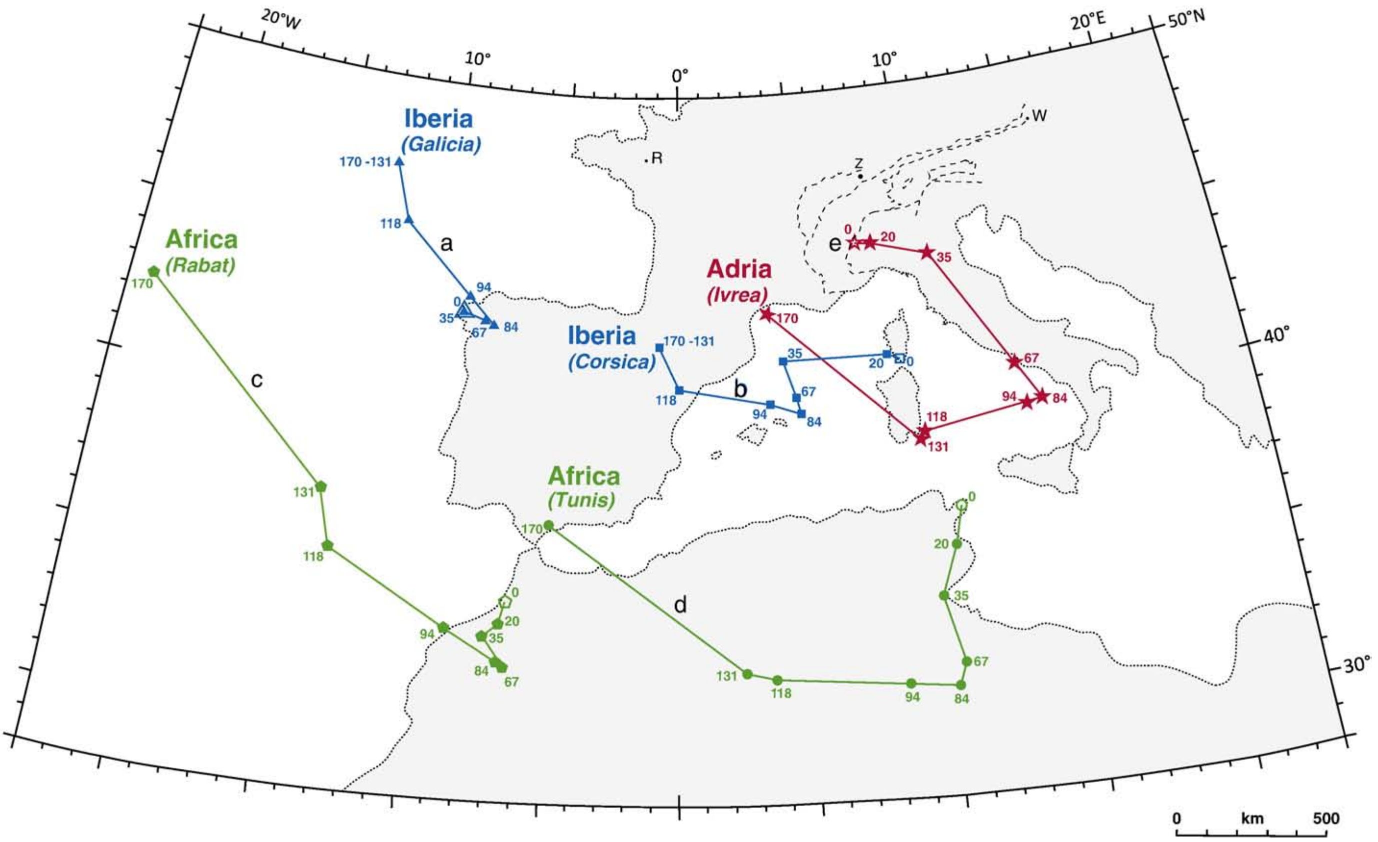


Fig. 7. Motion paths of five points labelled a to e located on tectonic plates and constructed according to criteria discussed in the text (Sections 3.2 and 3.3). Equal-area map projection modified from Capitanio and Goes (2006). Scale shows linear distances for center of map and is valid at the map edges to within 0.5 mm (6.8 km). Dotted lines = present coastal outlines. Dashed lines = Alpine nappe edifice. City locations for reference on stable Europe: R = Rennes, W = Wien (Vienna), Z = Zürich.

Tethys, as well as on the width of these domains, as discussed below in Section 4.2.1. Although Late Cretaceous crustal thinning is documented before the Pyrenean Orogeny (Lagabrielle and Bodinier, 2008), there is no geological evidence to indicate the formation there of oceanic crust (e.g., Choukroune, 1992; Wortmann et al., 2001).

Point b (Corsica) is initially located along the eastern border of Iberia in accordance with the reconstructions of Frisch (1979) and later of Stampfli and Borel (2002). We note that this location at 170 Ma is further to the SE than in most reconstructions for this time and is necessary in order to allow sufficient distance from point e (Ivrea) on the Adriatic margin for subsequent spreading of the Piemont–Liguria Ocean. Point b remains equidistant from point a (Galicia) until 35 Ma, reflecting clear evidence that Corsica, together with Sardinia and the Balearic islands, was part of the Iberian plate until latest Eocene time (e.g., Séranne, 1999). This marks the onset of Oligocene to early Miocene (Aquitanian) rifting of the Corsica–Sardinia block from the rest of Iberia, followed by Burdigalian opening of the Liguria–Provençal Basin (Séranne, 1999). Post-Oligocene motion of point b is relevant only for the final plate reconstruction at 20 Ma.

Point e is located at the northwestern extremity of the Adriatic plate and marks the city of Ivrea in the Ivrea Zone (Fig. 4). The Ivrea Zone exposes deep crustal rocks as part of a coherent crustal cross section through uppermost mantle and lower crust that was emplaced into the upper continental crust in Early Jurassic and Cenozoic times (e.g., Zingg et al., 1990). Point e also lies south of the Cenozoic mylonite belts of the Periadriatic Line bordering the arcuate retro-wedge of the Alpine orogen and is therefore unaffected by penetrative, ductile Alpine deformation (e.g., Handy et al., 1999). Point e in the Ivrea Zone is therefore a convenient marker in our reconstruction. It also coincides broadly with estimated locations of the Miocene rotation pole for Adria as determined from geodetic studies (e.g., Nocquet and Calais, 2004) and from retrodeformation of the Southern Alps (Schmid and Kissling, 2000), Carpathians, Pannonian Basin and northern Dinarides (Ustaszewski et al., 2008). Prior to the onset of spreading in the Piemont–Liguria Ocean, the Ivrea Zone occupied the northwestern, distal passive margin of the Adriatic microplate (e.g., Handy and Zingg, 1991), as discussed in detail below.

The locations of point e in Fig. 7 are crucial, as they prescribe the motion of an independent Adria microplate with respect to stable Europe. They are fixed according to a series of retrotranslations summarized in Table 1 that extend from the present to the onset of spreading of the Piemont–Liguria Ocean basin at about 170 Ma. Retrotranslations are taken to be displacements of point e backward in time on the map surface. Backrotations are a series of rotations backward in time that were performed about a vertical axis located at the various positions that point e reached during its stepwise retrotranslation. The retrotranslations of point e back to 94 Ma are

Table 1
Retrotranslation and backrotation of Adria with respect to stable Europe.
Sources: (1) Lippitsch et al. (2003); (2) Schmid and Kissling (2000); (3) Márton et al. (2010); (4) Ustaszewski et al. (2008); (5) references for stretching lineations in Fig. 5; (6) Babist et al. (2006); (7) Dal Piaz and Zirpoli (1979); (8) Molli (2008).

Step	Age interval (Ma)	Retrotranslation (distance/azimuth)	Backrotation (°)
1	0–35	243 km(1)/105°(2)	20° clockwise(3,4)
2	35–67	465 km(2)/150°(5)	
3	67–84	150 km(6)/150°(5)	5° clockwise(3)
4	84–94	50 km(7)/265° (8)	4° clockwise(3)
5	94–118	350 km/265°	11° clockwise(3)
6	118–131	50 km/240°	10° clockwise(3)
7	131–170	652 km/300°	9° clockwise(3)

constrained primarily by estimates of shortening in the Central Alps from geological–geophysical transects of the Alpine orogen and from geobarometric estimates of subduction depth in tectonic units that underwent high-pressure and ultrahigh-pressure metamorphism.

The following assumptions underlie the retrotranslations and backrotations listed in Table 1: (1) The rotation pole for motion of Adria with respect to Europe from the present time back to 94 Ma is sited at point e (Ivrea) due to the lack of significant crustal deformation south of this point. In the absence of evidence to the contrary, this assumption is convenient because rotations of Adria about point e obviously do not affect the translation path of this point; (2) the amount of backrotation of Adria with respect to Africa is taken from the sources listed in Table 1. We note that direct geological evidence for the rotation of Adria extends only back to the last 20 Ma in the Alps–Pannonian–Carpathian–Dinaric region (Ustaszewski et al., 2008); earlier rotations are based on a combination of magnetic anomalies in the Central and Northern Atlantic (Westphal et al., 1986 used in Savostin et al., 1986) and from the terrestrial paleomagnetic data (Márton et al., 2010); (3) The Tunisian peninsula (Pelagian Block) and southeastern Sicily (Hyblean Platform) remain fixed with respect to each other throughout the reconstruction. This reflects the fact that Tunis and southern Sicily are both part of stable Africa and have been largely unaffected by deformation since 170 Ma; (4) the eastern coast of Italy between Trieste and Apulia represents a part of the Adriatic microplate that has moved independently of both Africa and Europe since at least Early Cretaceous time. We note that prior to 84 Ma, point e on the Adriatic microplate is retrotranslated together with Africa; geological evidence reviewed below indicates that during this time the relative motions of Adria with respect to Africa are explained sufficiently by rotations about point e.

The steps for reconstructing the motion path of point e in Fig. 7 (summarized in Table 1) are based on the following arguments and assumptions:

Step 1 involves the 243 km retrotranslation of point e (Ivrea) from 0 to 35 Ma, 30 km of which are estimated to have occurred since 20 Ma (Ustaszewski et al., 2008). This translation was derived from the estimated 63 km of post-Eocene N–S shortening in the NPF20E profile across the eastern Central Alps north of the Insubric Line (Schmid et al., 1996) resolved onto the average azimuth (105°) of Oligo-Miocene and younger stretching lineations and kinematic indicators measured in the northern part of the Western Alps (Ceriani et al., 2001; some of the red arrows shown in Fig. 5). Lineations in the southern part of the arc of the Western Alps were strongly re-oriented during Oligo-Miocene counter-clockwise oroclinal bending (Collombet et al., 2002) and hence were not used here. The 243 km of WNW–ESE directed shortening thus obtained is identical—within the limits of uncertainty—with an estimated 240 km of collisional shortening across the French–Italian Western Alps obtained independently from the approximate length of the detached European slab beneath the ECORS-CROP transect (Fig. 3a; Lippitsch et al., 2003). We note that this estimate is greater than that usually cited for post-Eocene dextral motion on the Periadriatic Fault System (100–150 km, Schmid and Kissling, 2000; Handy et al., 2005 and references therein) but somewhat less than the 300 km proposed by Laubscher (1971) based on the presumed post-Eocene offset of subduction zones with opposite polarity in the Eastern Alps and Dinarides.

Step 2 is a 465 km retrotranslation of point e between 35 and 67 Ma (Fig. 7). This amount of translation was obtained by resolving the estimated 400 km of Paleocene–Eocene, north–south shortening in the NFP20E profile of the eastern Central Alps (Schmid et al., 1996) onto the 150° average azimuth of stretching lineations formed during Late Cretaceous to Early Cenozoic, high-pressure (HP) and ultra-high-pressure (UHP) metamorphism in the Alps (green arrows, Fig. 5).

Step 3 from 67 to 84 Ma translates point e another 150 km parallel to the same 150° azimuth as in step 2. This direction coincides with the average direction of Late Cretaceous stretching lineations in HP-metamorphic rocks of the Sesia Zone (Vuichard, 1989). 150 km is a minimum estimate, as it corresponds to the sum of subduction depths obtained from the baric peaks of HP metamorphism in the three largest basement nappes of the Sesia Zone (Babist et al., 2006), each of which may consist of several tectonic slices. Nevertheless, it is roughly compatible with a 100 km total of Late Cretaceous N–S shortening in a more eastern N–S transect of the Alps, namely ≤35 km of Orobic S-directed thrusting in the Bergamasc part of the Southern Alps (Fig. 4, Schönborn, 1992) plus 54 km of Late Cretaceous (90–72 Ma) thrusting in the Northern Calcareous Alps (Eisbacher et al., 1990).

Step 4 involves 50 km of displacement of point e between 84 and 94 Ma. This is the estimated amount of shortening between Iberia and Adria and represents the difference between 100 km of ESE-directed motion of Iberia with respect to Europe and 50 km of convergence between Iberia and Adria as obtained from the petrologically constrained depth of subduction (Dal Piaz and Zirpoli, 1979) of 84 My-old eclogites in Alpine Corsica (Lahondère and Guerrot, 1997; Malavieille et al., 1998).

Steps for times prior to 94 Ma entail the assumption that point e (Ivrea) on the Adriatic microplate moved together with Africa. This is justified in light of the lack of any geological evidence (HP metamorphism, orogenic flysch) for differential motion between these two plates prior to 94 Ma, except for rotations that account for limited extension in the Ionian Sea as discussed below. The minor jog in Adria's path between 118 and 131 Ma (Fig. 7) therefore reflects the close proximity of point e to the rotation pole for Africa during this time.

The approach adopted above for reconstructing Adria's motion path has an uncertainty of several tens of kilometers for each retrotranslation and of up to 10° for each backrotation (Márton et al., 2010). Despite this poor accuracy, we note that conventional plate-kinematic reconstructions based solely on ocean-floor magnetic anomalies, paleomagnetic data, and hot-spot tracks rest on equally shaky foundations, as discussed below in Section 3.3. Our approach results in a Cretaceous-to-Present motion path for Adria that is independent of Africa's path, in contrast to the single motion path for a coherent African–Adriatic plate in reconstructions based on ocean-floor magnetic anomalies (e.g., Dewey et al., 1989) and assumed in most subsequent kinematic models.

3.3. Methods used and their limitations in plate-motion reconstructions

Before proceeding with a detailed description of the reconstructions in Section 4, we recall some of the limitations of the methods used in our approach, indeed in all reconstructions for tectonic systems that experienced prolonged subduction and complex plate motions. We used the following three independent methods in a complimentary fashion to compensate for their individual shortcomings:

Method 1 entails plate-kinematic reconstructions (e.g., Savostin et al., 1986; Dewey et al., 1989; Royer et al., 1992; Olivet, 1996; Rosenbaum et al., 2002a) that are based on oceanic magnetic anomalies, analyses of fracture zones and hot-spot tracks, and magnetic pole paths on stable parts of continents. The basic limitation in applying such reconstructions too literally to geology is that they treat all motions, including those involving ductile deformation of the deep crust and mantle, as rigid-body translations and rotations. Furthermore, they involve interpolating plate motions over large gaps in the magnetic rock record, for example, the long interval between Late Cretaceous reversals in the Central and North Atlantic ("Cretaceous Quiet Magnetic Zone" or

"Cretaceous Normal Superchron", CNS between Anomalies 34 and M0 from 120 to 83 Ma, Rosenbaum et al., 2002a). An additional problem affecting reconstructions of Alpine Tethys is the lack of clear linear magnetic anomalies in the Western Mediterranean, which so far, have only been identified in the Western Mediterranean fossil rift (Bayer et al., 1973). This probably reflects the formation of Mediterranean ocean basins by extensional exhumation of subcontinental mantle rocks, with only limited sea-floor spreading (e.g., Lemoine et al., 1987; Kastens et al., 1988). Finally, not all continental platforms used for magnetic pole studies of Adria are as undeformed as previously thought; recent motion studies have revealed that Adria is currently rotating independently of its surrounding plates (e.g., Nocquet and Calais, 2004; Vrabec et al., 2006) at a rate of 0.2–0.9°/My (Grenerczy et al., 2005). When extrapolated back in time, this range of rotation rates corresponds to between 7° and 31° of independent rotation during the last 35 My. Indeed, divergent GPS-derived motion vectors for Africa (southeastern Sicily) and Adria (Apulia, Dinaric coast) indicate a component of tension across a putative plate boundary in the vicinity of the Ionian Sea. This is substantiated by direct geophysical evidence for graben structures in the Sicily Channel between Tunis and southern Sicily (Fig. 1) currently forming during NE–SW directed extension (Corti et al., 2006).

Method 2 involves reconstructing basin geometry and subsidence history from stratigraphic data, assisted by analysis of the clastic content of sediments and facies analysis. This approach provides the most reliable record of tectonics at the surface. Unfortunately, the rock record is seldom complete, especially after subduction, which eliminates oceanic lithosphere more readily than transitional or continental lithospheres. This selectivity is also manifested as gaps in stratigraphy (erosional unconformities, disconformities), reworking (including redeposition of fossils, yielding apparently older ages of sedimentation) and overprinting by later deformation and metamorphism. Nevertheless, there is consensus that orogenic flysch and associated deep-water conglomerates and tectonic mélange ("Wildflysch" in the Alpine literature) indicate proximity to an accretionary wedge and an encroaching trench. We therefore used the age of the youngest rocks (often also flysch or mélange) below a tectonic contact, and the oldest rocks just above this contact to constrain the oldest possible age of emplacement of the overlying thrust sheet. We note that not all flysch-like mass-flow deposits, including terrigenous turbidites, are related to active convergent tectonics; indeed, turbiditic sequences can derive from anorogenic sources far away from accretionary wedges and travel long distances parallel to the basin axis (Mutti et al., 2009). In the case of the Alps, only turbidites with immature sandstones whose detrital grains can be traced to source areas within the subduction–accretion complex are considered to be proxies for tectonically induced erosion.

Method 3 combines structural, petrological and geochronological information to reconstruct the kinematic history of metamorphosed crustal rocks. This approach is limited by the selective preservation of metamorphic mineral assemblages due to later thermal and deformational overprinting. The polyphase deformation and metamorphism of such rocks makes dating individual minerals difficult and often yields ambiguous mineral ages that can be interpreted either as ages of formation, cooling ages or mixed ages (Berger and Bousquet, 2008). This is especially true of high-pressure (HP) blueschist- and eclogite-facies and ultra-high pressure (UHP) coesite-bearing mineral assemblages, which have sluggish reaction kinetics at relatively low temperatures along subduction geotherms. Isotopic systems that potentially date a HP event are susceptible to resetting during subsequent thermal events or hydrothermal activity (e.g., Hammerschmidt and Frank, 1991). To circumvent this problem, we cite primarily ages that were obtained from high-retentivity isotopic systems (e.g., Lu–Hf and Sm–Nd isochrons from calcic garnet and coexisting HP phases). Similar ages for HP metamorphism are sometimes obtained from the SHRIMP method applied to the U–Pb system in zircon, but we regard these ages with caution because the spot analyses within chemically zoned zircons cannot always be related unequivocally to the growth history of HP phases in the host rock. There is a tendency in the Alpine literature to interpret an apparently robust isotopic age as dating an individual tectonic event (e.g., individual ages dating alternating episodes of subduction and extension, Liati et al., 2003a; Rosenbaum et al., 2004). In actuality, each age dates the equilibration of an isotopic system at a single point in space and time during a longer, larger-scale tectonothermal event. Such an event, for example subduction of Alpine Tethys, lasted for several millions of years on the scale of the lithosphere. Therefore, we interpret similar ages (within error) from different high-retentivity systems and from a suite of samples taken from related tectonic units in terms of a continuous subduction event, especially where this is corroborated by a similar range of clastic sediment ages.

4. Motion history of microplates in Alpine Tethys

The maps and cross sections presented below depict plate configurations with respect to a stable Europe, from the beginning of sea-floor spreading in the Piemont–Liguria basin (Figs. 8 and 9), through the progressive subduction of Neotethys and Alpine Tethys (Figs. 10–13), to Alpine collision and the formation of the Western Mediterranean (Figs. 14 and 15). The overall plate motions are constrained by the paths of the points depicted in Fig. 7 (also shown as reference points in Figs. 8, 10, 12, and 14). Details in the maps and sections are based on geological and petrological information regarding the amounts and timing of shortening and subduction (Fig. 6). Fig. 16 summarizes the rates and directions of divergence and convergence between Europe, Iberia, Adria and Africa that result from changes in distance between reference points a–e shown in Fig. 7. The thickness of the oceanic lithosphere in the cross sections is based on the age–thickness relationship of Parsons and Sclater (1977): Lithospheric thickness, d, increases with age A (My) according to the relation d = 11sqrA, and lithosphere that is older than 80 My has attained a constant (i.e., age-independent) thickness of 100 km.

4.1. Motion of Africa leading to opening of the Piemont–Liguria Ocean and contemporaneous subduction/obduction of the Vardar Ocean

Fig. 8a shows the plate-tectonic situation at the onset of spreading at 170 Ma, when Alpine Tethys opened as a spur or offshoot of the Central Atlantic in response to sinistral transcurrent motion of Africa with respect to Europe (Le Pichon, 1968; Dewey et al., 1973; Laubscher and Bernoulli, 1977). Initially, Adria was a promontory attached to Africa and the future Iberian plate was still attached to Europe. Alcapia and Tiszia were about to individuate as microplates to the north of a large E–W-trending transform fault, inferred to have connected spreading of Alpine Tethys with intra-oceanic subduction of the northern branch of Neotethys (Meliata–Maliac and Vardar) east of the area depicted in Fig. 8a. A part of this transform fault was the Mesozoic predecessor of the Cenozoic Periadriatic or Insubric Line, which currently separates the Austroalpine nappes from the unmetamorphic Southern Alpine units (Figs. 4 and 5).

Rifting and tectonic subsidence began in earnest in Early Jurassic time (Hettangian, 200–197 Ma, Fig. 6), although pronounced facies and thickness variations in Upper Triassic sediments of the Adriatic, Iberian and European margins indicate that limited extension began earlier (e.g., Bertotti et al., 1993; Froitzheim and Manatschal, 1996). Evidence for even earlier rifting is ambiguous and based largely on the occurrence of Middle Triassic shoshonitic to calc-alkaline volcanics in

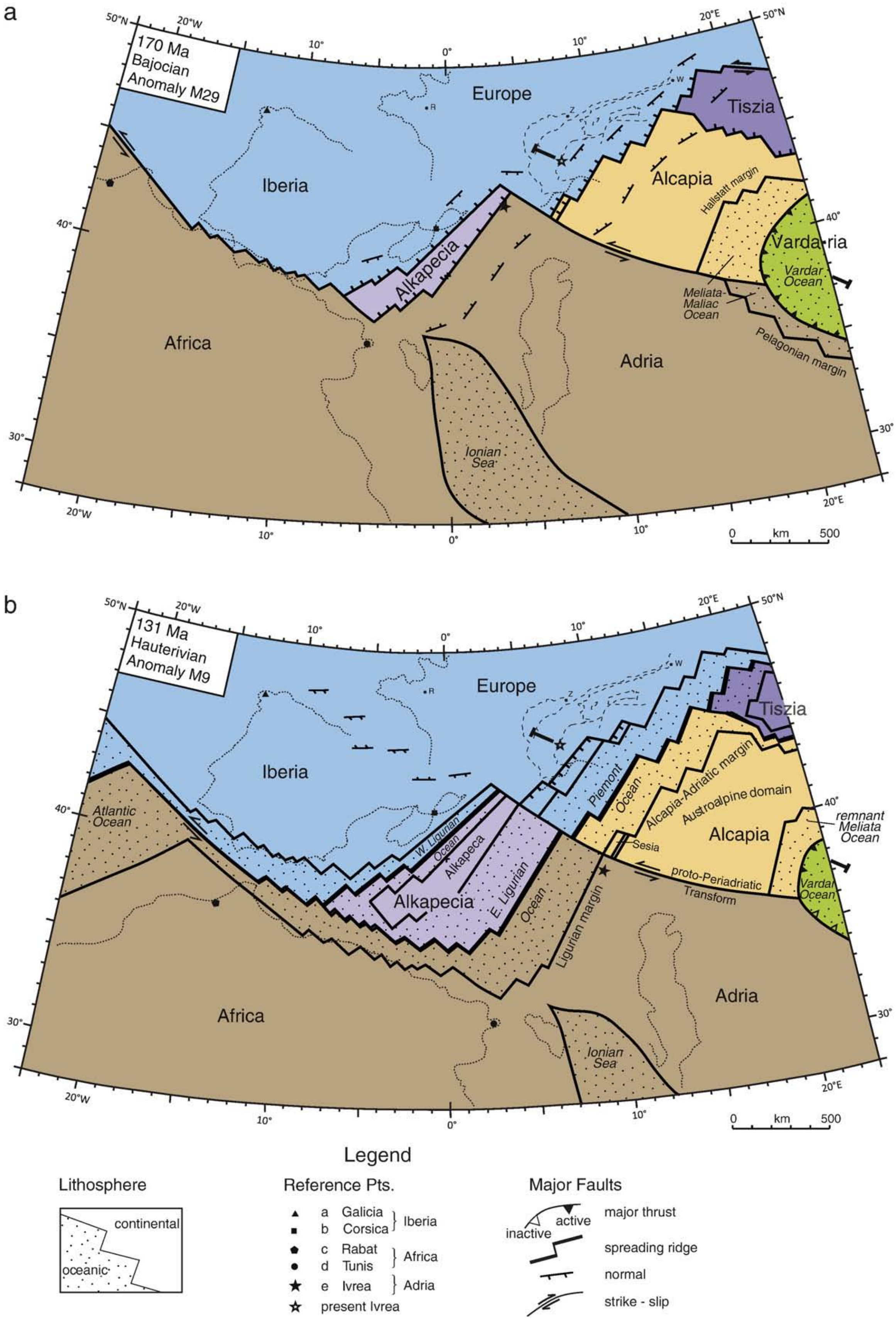


Fig. 8. Plate tectonic maps of Alpine Tethys and the western embayment of Neotethys: (a) 170 Ma, Africa, Alcapia and Tiszia break away from Europe; the Jurassic Vardar Ocean is obducted westward onto Triassic Meliata–Maliac oceanic crust; (b) 131 Ma, end of spreading in the Piemont–Liguria Ocean. A sinistral transform fault links this spreading with subduction and obduction of Vardar oceanic crust. Line shows trace of cross sections in Fig. 9. Dotted lines = coastal outlines of Western Europe, Iberia, islands in the Western Mediterranean Sea (Corsica, Sardinia), southernmost Italy (Apulia) and northern Africa. Dashed lines = current outline of Alpine nappe edifice. City locations for reference on Europe: R = Rennes, W = Wien (Vienna), Z = Zürich.

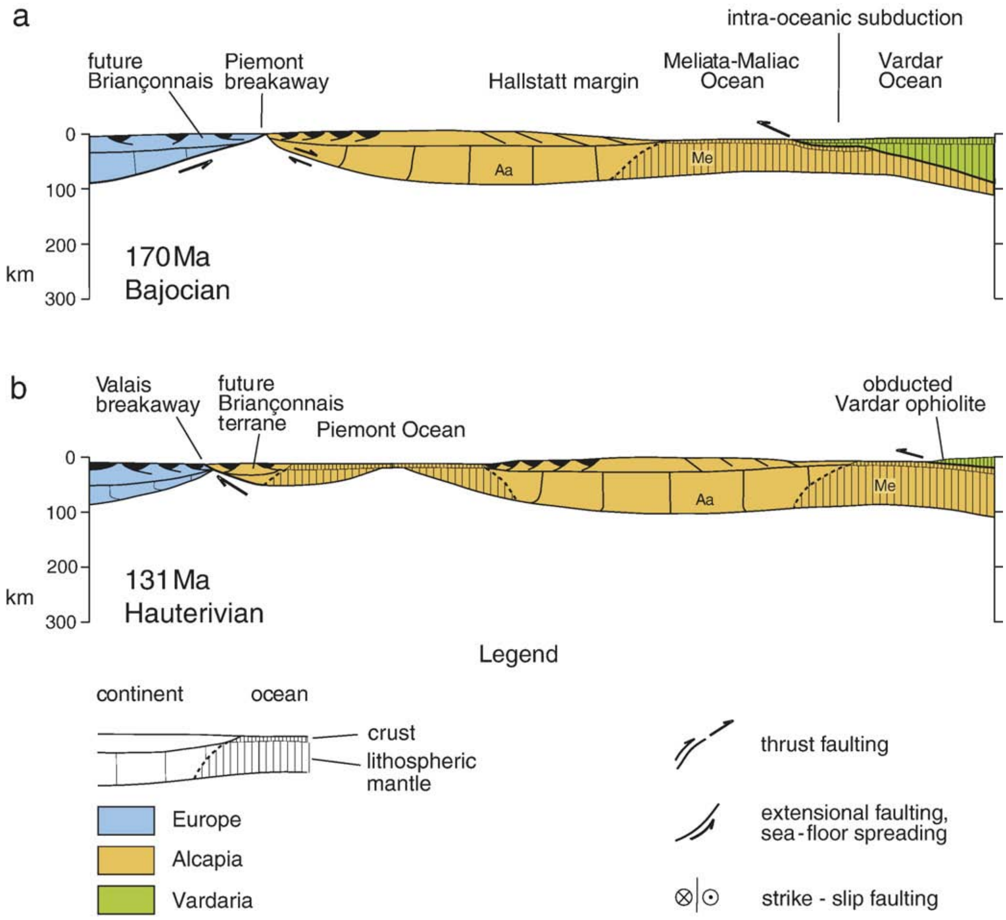


Fig. 9. Cross sections through Alpine Tethys and part of Neotethys: (a) 170 Ma, onset of spreading in Piemont part of Alpine Tethys; intra-oceanic obduction of Vardar oceanic lithosphere; (b) 131 Ma, end of spreading in Piemont part of Alpine Tethys and onset of Eo-alpine orogenesis; Location of cross sections shown in Fig. 8. Horizontal scale equals vertical scale. Aa = Austroalpine (Alcapia) continental lithosphere, Me = Meliata–Maliac oceanic lithosphere.

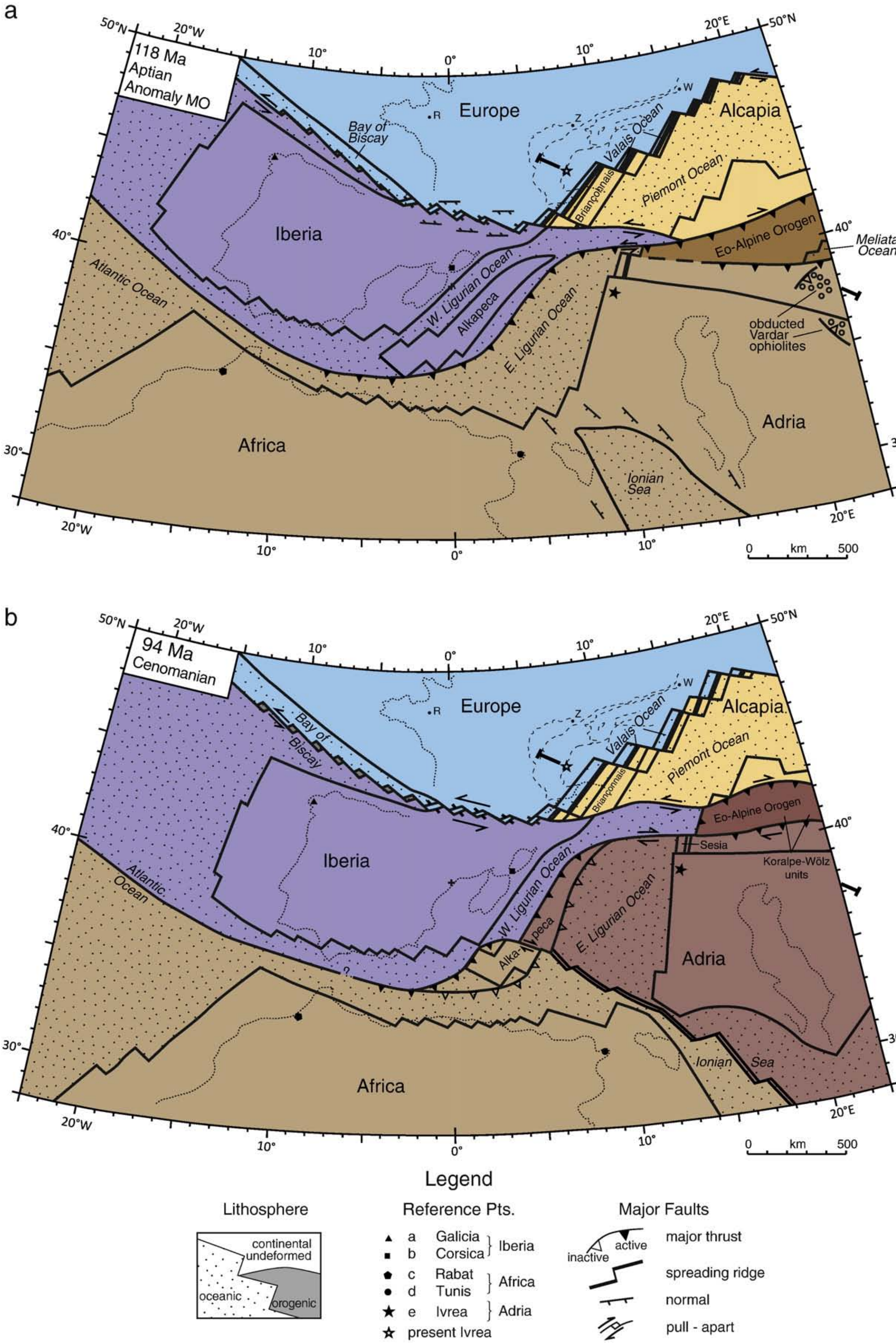
the Southern Alps. This magmatic event has been interpreted as related to extensional (Crisci et al., 1984) or strike-slip tectonics (Sloman, 1989), but in either case it was probably associated with the development of the Hallstatt margin during Triassic opening of Neotethys (Meliata–Maliac Ocean) rather than of Alpine Tethys.

Early Jurassic rifting was non-volcanic and asymmetric, with the lower plate to the breakaway normal fault located on the eastern, Adriatic margin (Fig. 9a, Lemoine et al., 1987; Froitzheim and Eberli, 1990; Manatschal and Bernoulli, 1999). The end of rifting is marked by the deposition of Bajocian–Bathonian (172–165 Ma) post-rift, pelagic sediments (Baumgartner et al., 1995; Stampfli et al., 1998; Bill et al., 2001). A still unquantified amount of extension during the transition from rifting to slow sea-floor spreading involved the exhumation and serpentinization of subcontinental mantle at the Piemont–Liguria Ocean margins (e.g., Desmurs et al., 2001). The width of continental margins affected by rifting was as much as 240–300 km according to Lavier and Manatschal (2006).

By the end of rifting, the Ivrea Zone within the distal Adriatic passive continental margin was located not far from the original location of the northern tip of Corsica, adjacent to the distal European passive margin (point e in Figs. 7 and 8a). Note that the location of point e in Fig. 8a (Ivrea Zone) is that given by the retrotranslations defined in Fig. 7 and determines the final estimated width of the Piemont–Liguria Ocean. Larger estimates of the amount of Cretaceous–Cenozoic shortening in the Alps would place point e further away from Europe and allow oceanic widths greater than the approximately 800 km shown in Fig. 8b. In fact, our shortening estimates represent a minimum, making the location of point e at 170 Ma ago as shown in Figs. 7 and 8a somewhat too close to the coast of present-day southern France.

Spreading of the Piemont and Liguria Oceans that are separated from each other by a large E–W-trending transform fault (Fig. 8b), collectively referred to as the Piemont–Liguria Ocean, began at about 170 Ma. This is in accordance with the earliest 170–160 My magmatic zircon crystallization ages from ophiolites (Lombardo et al., 2002; Schaltegger et al., 2002 and references therein). Spreading is inferred to have ended when transform activity jumped northwards with the incipient opening of the southern North Atlantic (between Iberia and Newfoundland) and the Bay of Biscay at about 131 Ma (Fig. 8b). This inferred age for the end of spreading is significantly younger than the youngest U–Pb ages (141–148 Ma) of magmatic zircons in Piemont–Liguria ophiolites of the Central (Liati et al., 2003a,b) and Western Alps (Costa and Caby, 2001) and also post-dates Oxfordian–Tithonian pelagic sediments preserved on relics of oceanic crust (Bill et al., 2001; Lombardo et al., 2002; Schaltegger et al., 2002 and references therein). Note, however, that such relics are invariably found in ocean–

Fig. 10. Plate tectonic maps of Alpine Tethys and adjacent continental margins during Late Cretaceous time: (a) 118 Ma, sinistral transform motion of Iberia linked to Eo-alpine orogenesis and spreading in the Valais Ocean; intra-oceanic subduction of eastern Ligurian Ocean; (b) 94 Ma, end of spreading in the Valais Ocean, ongoing Eo-alpine orogenesis including HP metamorphism, incipient subduction of western Ligurian and eastern Piemont Ocean. Line shows trace of cross sections in Fig. 11. Dashed lines = current outline of Alpine nappe edifice. City locations for reference on Europe: R = Rennes, W = Wien (Vienna), Z = Zürich.


a
118 Ma
Aptian
Anomaly MO
Europe
Bay of Biscay
Alcapia
Valais Ocean
Briançonnais
Piemont Ocean
Eo-Alpine Orogen
Meliata Ocean
Iberia
W. Ligurian Ocean
Alkapeca
E. Ligurian Ocean
Atlantic Ocean
obducted Vardar ophiolites
Africa
Adria
Ionian Sea
b
94 Ma
Cenomanian
Europe
Bay of Biscay
Valais Ocean
Alcapia
Piemont Ocean
Briançonnais
Eo-Alpine Orogen
Sesia
Koralpe-Wölz units
Iberia
W. Ligurian Ocean
Alka-peca
E. Ligurian Ocean
Atlantic Ocean
Adria
Africa
Ionian Sea
0 km 500
Legend
Lithosphere
continental undeformed
oceanic
orogenic
Reference Pts.
a Galicia
b Corsica
Iberia
c Rabat
d Tunis
Africa
e Ivrea
Adria
present Ivrea
Major Faults
inactive
active
major thrust
spreading ridge
normal
pull - apart

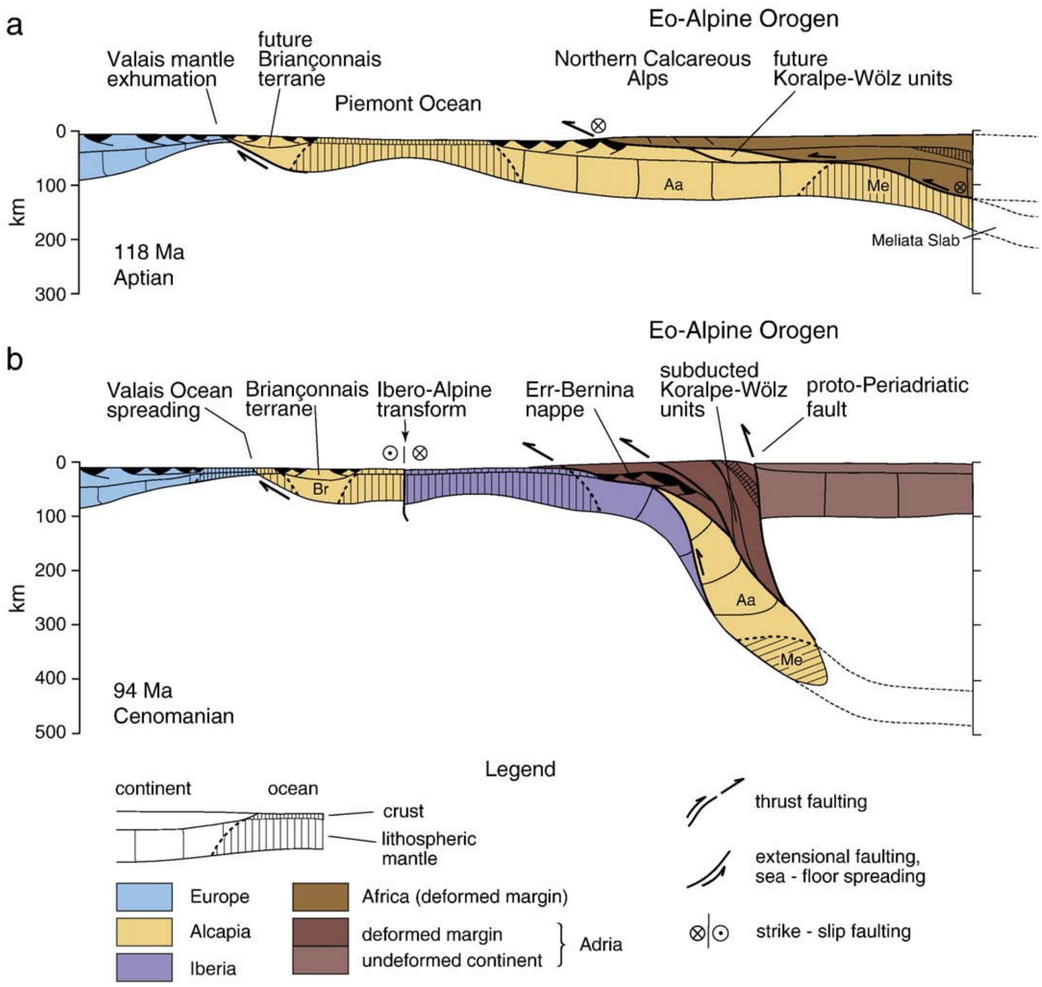


Fig. 11. Cross sections through Alpine Tethys and adjacent continental margins in Late Cretaceous time: (a) 118 Ma, spreading of Valais Ocean linked to Eo-alpine orogenesis, with dashed lines showing probable eastward continuation of the Adriatic lithosphere and the subducted slab of Alcapia (including Meliata oceanic lithosphere); (b) 94 Ma, onset of active margin tectonics only at western end of Eastern Alps due to convergence of Iberia and Alcapia; intracontinental subduction in Eastern Alps. The dashed lines indicate the lateral continuation of the slab of Neotethyan (Me = Meliata–Maliac) oceanic lithosphere behind, i.e., ENE of the plane of the cross section. Location of cross sections shown in Fig. 10. Horizontal scale equals vertical scale. Aa = Austroalpine (Alcapia) continental lithosphere, Br = Briançonnais continental fragment, Me = Meliata–Maliac oceanic lithosphere.

continent transitional units, indicating that they derived from the edges rather than the younger, median parts of the former Piemont–Liguria Ocean. Subduction appears to have spared the oldest, marginal parts of the oceanic lithosphere, perhaps because serpentinization of the slowly exhuming subcontinental mantle rocks during rifting rendered them more buoyant and resistant to later subduction. Based on the timing constraints summarized in Fig. 6, sea-floor spreading of the Piemont–Liguria Ocean is inferred to have lasted for about 40 My, which yields an average rate of 2 cm/yr (Fig. 16), in good agreement with Early Jurassic to Early Cretaceous spreading rates of the Central and North Atlantic (e.g., Savostin et al., 1986; Dewey et al., 1989; Rosenbaum et al., 2002a). We note that local spreading rates are expected to have been much less than this average, especially in the northern part of the Piemont Ocean located closer to Africa's rotation pole, or in the narrow western branch of the Ligurian Ocean.

In distinguishing eastern and western Ligurian Oceans (Fig. 8b), we follow the arguments of Michard et al. (2002, 2006) and Molli (2008) in favour of a narrow fragment of continental lithosphere (Alkapeca, see Fig. 1) that formed part of the short-lived Early Mesozoic Alkapecia microplate located between parts of Europe (later Iberian microplate) and Africa (later Adriatic microplate). However, in contrast to Michard et al. (2002, 2006), we have made the western branch narrower in order to allow for a wider eastern branch that was affected by a large amount of Oligo-Miocene rollback subduction (some 1000 km, Section 4.4) in this area. The small width of the western Ligurian Ocean in our reconstruction also reflects the minor proven amount of Ligurian oceanic lithosphere subducted during Late Cretaceous–Cenozoic time (about 190 km, Section 4.2.3). Remnants of the western branch are preserved as small ophiolitic bodies in the Nevado-Filabrides of the Betic Cordillera (Trommsdorff et al., 1998; Puga et al., 2002, 2009), overlain by fragments of Alkapeca (Malaguides, Alpujarrides, Dorsale calcaire and their equivalents in the Rif; Michard et al., 2002). Remnants of the eastern branch are well preserved in the Ligurian oceanic units of the Apennines (e.g., Decandia and Elter, 1972; Molli, 2008). In Calabria, these oceanic remnants are overlain by a relic of the Alkapeca continental fragment (Bonardi et al., 2001).

A proto-Periadriatic transform system accommodated differential spreading of the Piemont and Liguria Oceans, which in Fig. 8b amounts to about 300–400 km of sinistral offset. We tentatively link this displacement to the east with eastward subduction and later obduction of the Jurassic (Vardar) part of Neotethys onto the Adriatic continental margin, as discussed below. The amount of Jurassic displacement on this sinistral transform fault is poorly constrained; some plate-kinematic reconstructions call for as much as 800–1000 km offset (Capitanio and Goes, 2006), but this is certainly too much in light of our smaller estimated width of the Piemont and Liguria Oceans. An offset of 300–400 km would have been sufficient to form a promontory at the northwestern edge of Adria (Fig. 8b, see also Channell and Kozur, 1997), making this margin a preferred site for

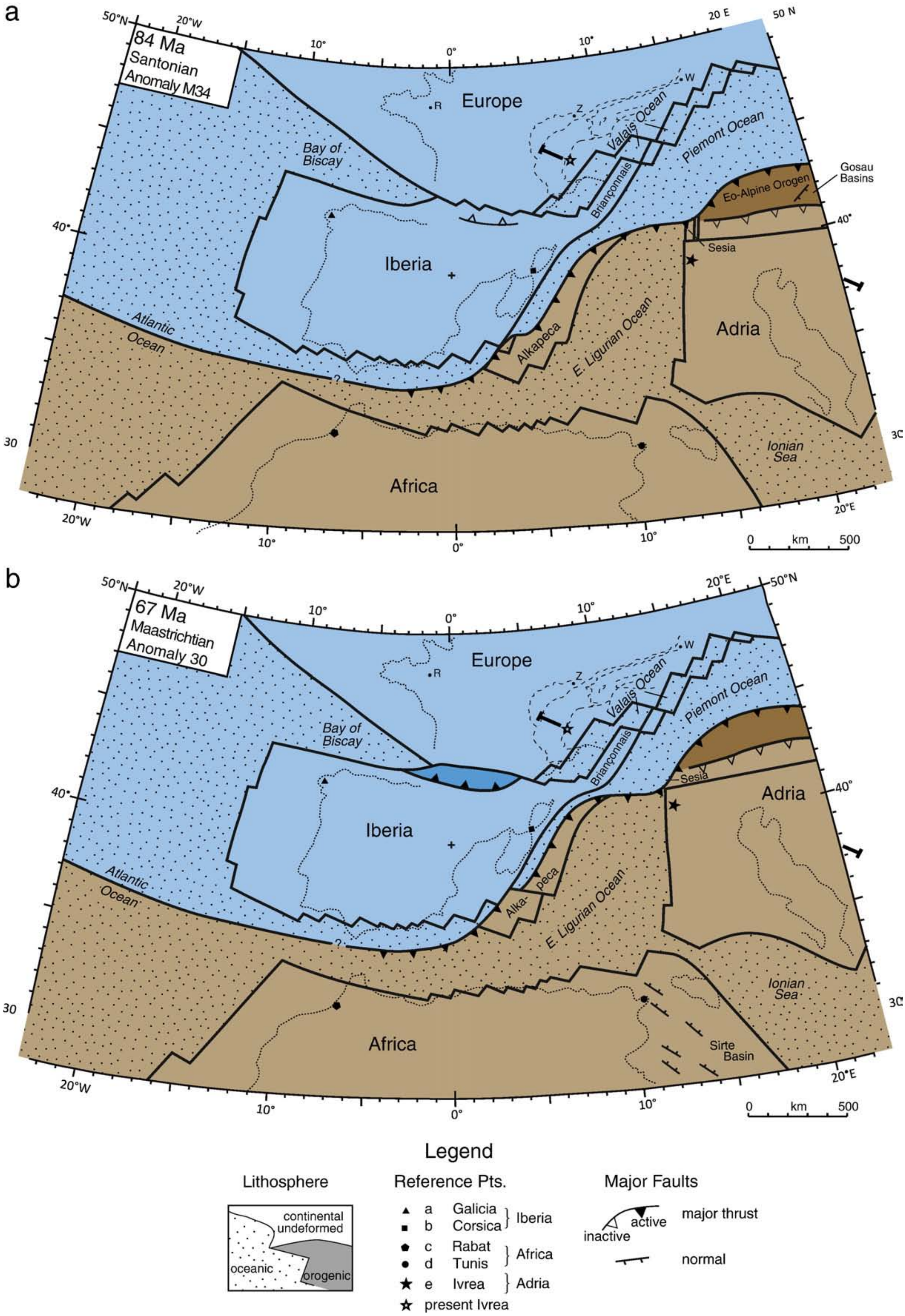


Fig. 12. Plate tectonic maps of Alpine Tethys and adjacent continental margins during NW motion of Africa: (a) 84 Ma, onset of S-directed subduction of Piemont Ocean along Eo-alpine active margin, continued subduction of western Ligurian Ocean; (b) 67 Ma, subduction of westernmost part of Austroalpine passive margin (Sesia Zone) and formation of Western Alpine accretionary wedge. Line shows trace of cross sections in Fig. 13. Dashed lines = current outline of Alpine nappe edifice. City locations for reference on Europe: R = Rennes, W = Wien (Vienna), Z = Zürich.

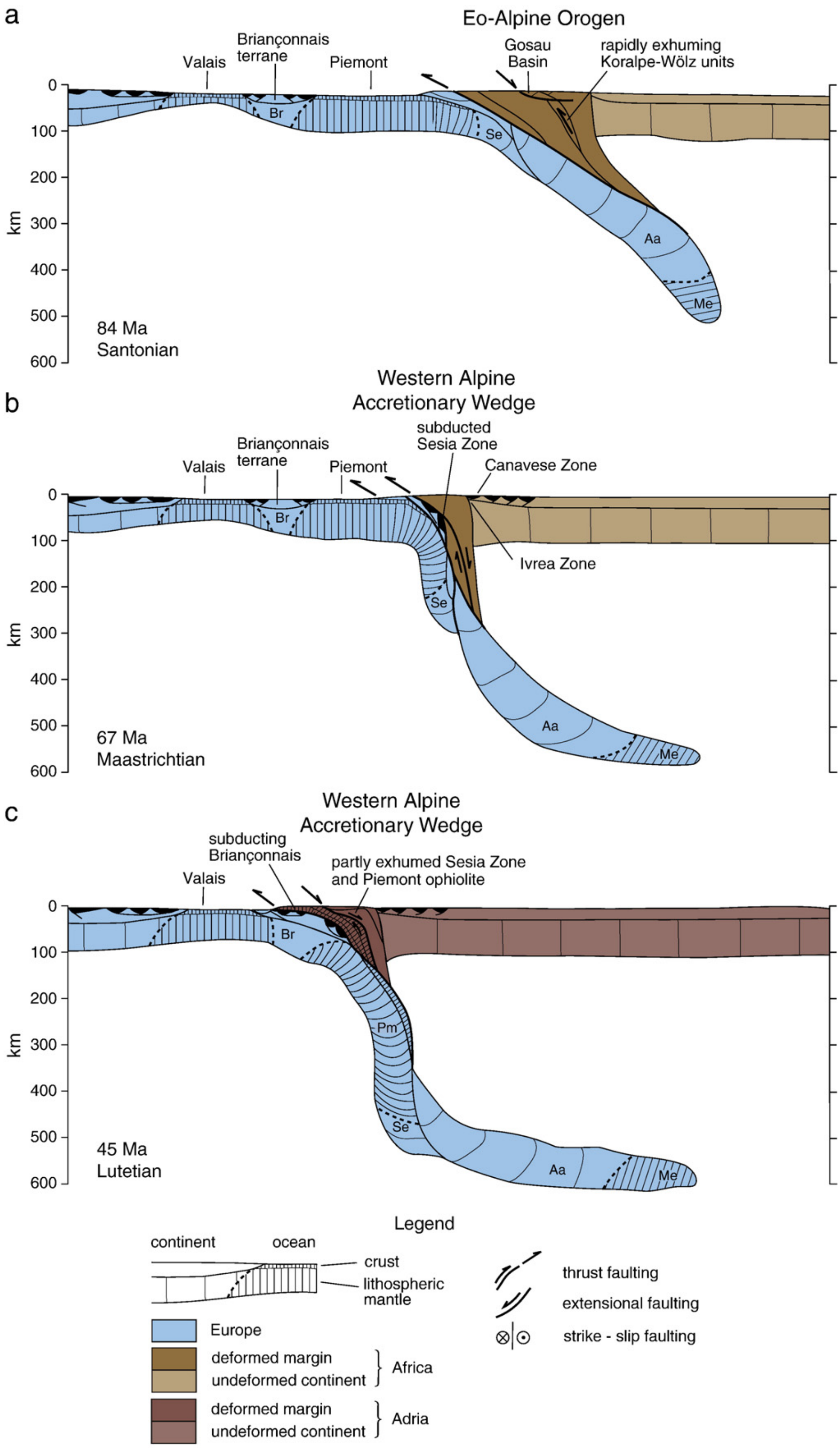


Fig. 13. Cross sections through Alpine Tethys during Late Cretaceous time: (a) 84 Ma, onset of subduction related to NW motion of Africa, rapid exhumation of Koralpe-Wölz unit; (b) 67 Ma, subduction of western tip of the Adriatic continental promontory (Se = lithosphere of the Sesia Zone) and formation of the Western Alpine accretionary wedge; (c) 45 Ma, Early Cenozoic accretion and imbrication of Piemont oceanic crustal slices, subduction of the Briançonnais continental fragment (Br). Location of cross sections shown in Fig. 12. Horizontal scale equals vertical scale. Aa = Austroalpine (Alcapia) continental lithosphere, Me = Meliata–Maliac oceanic lithosphere, Pm = Piemont oceanic lithosphere.

later subduction erosion at the onset of S-directed subduction of Alpine Tethys in Santonian time, as discussed in Section 4.3.1.

Sinistral transform faulting also affected other parts of the Alcapian continental margins in Jurassic time (Fig. 8a), for example, along the western margin the faulted contact between the future Lower and Upper Austroalpine nappes of eastern Switzerland (Froitzheim and Eberli, 1990; Froitzheim et al., 1994) and E–W trending faults that bound rift basins in Lower Austroalpine (Handy, 1996) and Southern Alpine units (Bertotti et al., 1993), as well as in the Northern Calcareous Alps (Channell et al., 1990; Gawlick et al., 1999; Frank and Schlager, 2006). Transform faulting and mantle exhumation continued during spreading of the Piemont–Liguria Ocean (Fig. 8b), as inferred from actualistic comparisons with oblique spreading in the Gulf of California (Kelts, 1981; Weissert and Bernoulli, 1985) and transpressional structures preserved in Briançonnais units (Schmid et al., 1990). The transform systems lent the lithosphere a strong E–W to WNW–ESE trending mechanical anisotropy that facilitated later subduction, as discussed in Section 4.2.3.

Jurassic intra-oceanic subduction of the Meliata–Maliac–Vardar Ocean along the eastern boundary of the Alcapia and Adriatic microplates (Figs. 8a and 9a) was followed by westward obduction of the Jurassic (Vardar) part of Neotethys onto distal elements of the Alcapian (Hallstatt) and Adriatic (Pelagonian) continental margins (Figs. 8b and 9b). This reconstruction for the Alcapian margin is admittedly speculative, as it is based on minor occurrences of Hallstatt- and Meliata-derived rock fragments and re-sedimented ophiolitic detritus preserved in the highest nappes of the easternmost Northern Calcareous Alps ("Distal Neotethyan margin (Hallstatt) and Neotethyan relics (Meliata)" in Fig. 4, Mandl and Ondrejicka, 1991; Kozur and Mostler, 1992), as well as on a comparison of these relics with ophiolites of the Carpathians, Dinarides and Hellenides (Schmid et al., 2008). In the Dinarides, mid-Jurassic intra-oceanic subduction (e.g., Pamić et al., 2002) is marked by a metamorphic sole at the base of the later-obducted ophiolites (Lanphere et al., 1975; Schmid et al., 2008). The Meliata–Maliac Ocean and Hallstatt margin were involved in accretionary wedge tectonics as early as in Late Callovian time (161 Ma, Gawlick et al., 1999), as documented by mélange containing blocks of Triassic ophiolites and pelagic sediment that were locally affected by blueschist-facies metamorphism (Faryad and Henjes-Kunst, 1997). Obduction of the Vardar oceanic lithosphere ended at about 145 Ma, when Kimmeridgian–Tithonian limestones sealed the Jurassic mélange and thrust contacts (Gawlick et al., 1999; Mandl, 2000). Thus, obduction halted along the distal eastern continental margins of Adria and possibly also of Alcapia (Figs. 8b and 9b) before the onset of the Eo-alpine Orogeny in Early Cretaceous time.

4.2. Cretaceous microplate motions and transform-dominated tectonics

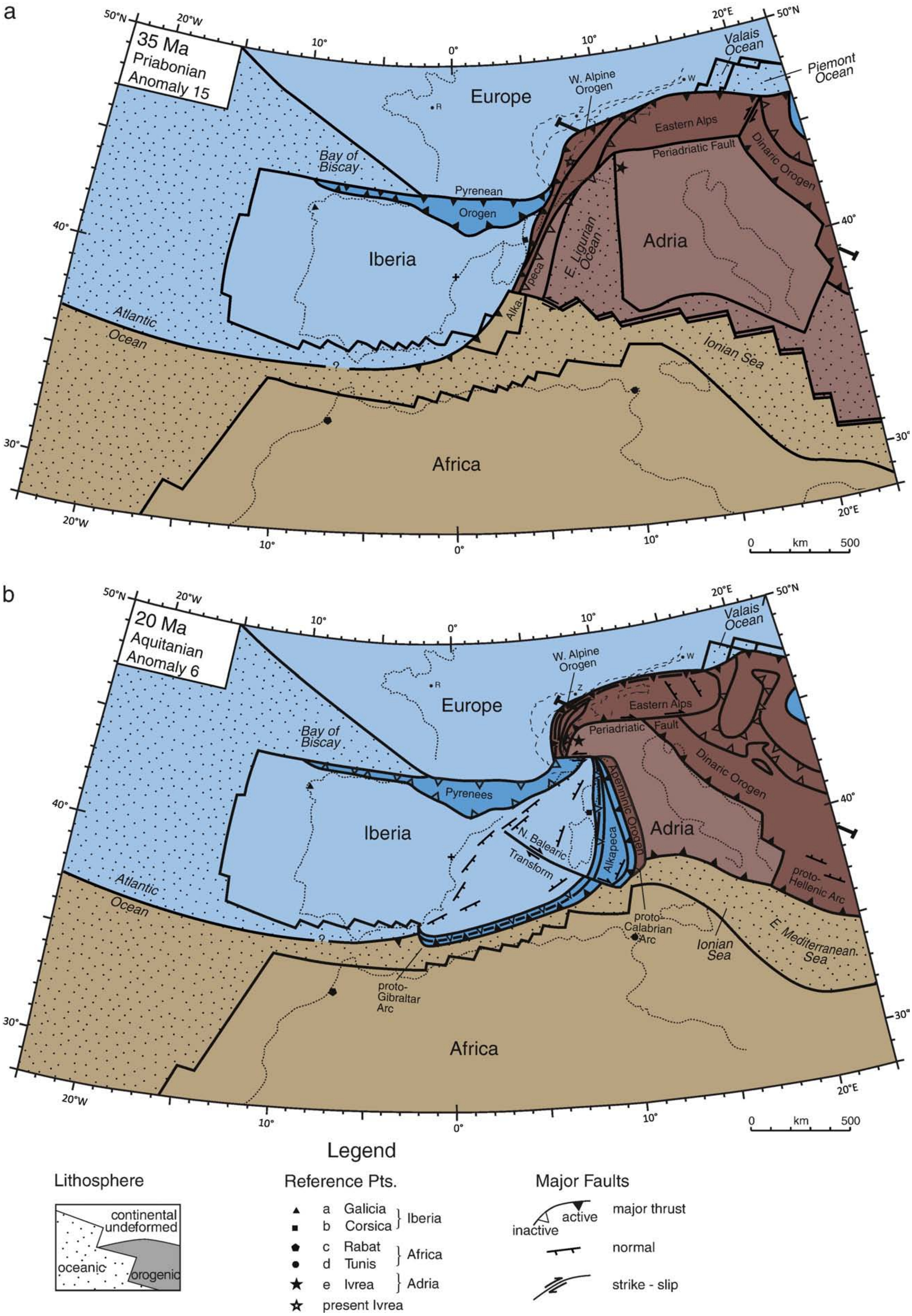
A transform scenario for the plate configuration in late Early Cretaceous (Aptian) time is shown in Fig. 10a. Beginning already at the turn of Jurassic to Cretaceous time (145 Ma), spreading of the Northern Atlantic Ocean started to jump northward to the Bay of Biscay, where the onset of spreading pre-dated the Aptian-age magnetic anomaly M0 (Stampfli et al., 1998). This led to the individuation and eastward motion of the Iberian microplate with respect to Europe, ending no later than 84 Ma according to most authors (e.g., Rosenbaum et al., 2002a; Capitanio and Goes, 2006). According to our reconstruction, this involved a total of 520 km of sinistral strike-slip sited along the future Pyrenees (Laubscher, 1975; Frisch, 1979; Stampfli, 1994), where local transtension is manifested by exposures of mantle rock that were exhumed within submarine pull-apart basins (Lagabrielle and Bodinier, 2008). Iberia's eastward motion coincided with the onset of subduction of the eastern Ligurian part of Alpine Tethys along the Iberian–African plate boundary (Fig. 10a), as Africa also moved eastward, but more slowly than Iberia according to our plate-motion paths in Fig. 7. We propose that this intra-oceanic subduction was laterally continuous with intra-continental subduction and Eo-alpine orogenesis (Figs. 10 and 11) at the northern tip of Adria, where Alcapia and Adria converged obliquely during the same time period. Also at that time, the site of spreading between Alcapia and Europe jumped westward, leading to opening of the narrow Valais Ocean and individuation of the Briançonnais continental fragment between the Valais and Piemont arms of Alpine Tethys (Figs. 10 and 11). The east-to-west paleogeographic configuration of these units shown in Fig. 10a and b is reflected today by the top-to-bottom stacking order of Early Cenozoic nappes in the Western Alps as well as by the position of these nappes beneath the Late Cretaceous Austroalpine nappes of the Eastern Alps (Fig. 4). As discussed below, E–W transform faulting played a crucial role in accommodating the contrasting amounts and rates of Cretaceous microplate motion.

4.2.1. Opening of the Valais Ocean

Following Steinmann (1994), we propose that rifting of the continental margins adjacent to the future Valais Ocean began as early as the Jurassic–Cretaceous boundary (146 Ma) and yielded to breakaway and sea-floor spreading no later than 130–125 Ma, the age of the oldest post-rift sediments (Upper Barremian–Lower Aptian, Schwizer, 1984) that seal low-angle normal faults and syn-rift sediments along the margins of the Valais Ocean (Engadine Window; Florineth and Froitzheim, 1994; Western Alps: Fügenschuh et al., 1999). Spreading continued until at least 93 Ma, the youngest age of magmatic zircons obtained so far from ophiolites of Valaisan affinity in the Alps (gabbro from the Chiavenna ophiolite, Liati et al., 2003a). A 130–93 Ma age range for spreading of the Valais Ocean (Fig. 6) coincides broadly with the range of ages for the counter-clockwise rotation of Iberia with respect to Europe (130–93 Ma, Srivastava et al., 1990; 131–83 Ma, Rosenbaum et al., 2002a), leading most workers to propose that the two events are kinematically related. However, the timing, amount and extent of Iberia's rotation are poorly constrained due to the proximity of the rotation poles for Iberia and Africa with respect to Europe (e.g., Gong et al., 2009 and references therein). The extent to which the opening of the Valais Ocean and the rotation of Iberia were actually linked depends on the relative amounts and rates of Valais spreading and transform faulting, as discussed further below.

The final width of the Valais Ocean at the end of spreading is inferred to have been about 100 km (Figs. 10b and 11b), but this amount is very poorly constrained. Other reconstructions have proposed either a narrower (50 km, Schmid et al., 2004a) or much wider Valais Ocean (>200 km, Rosenbaum et al., 2002a); a width of no more than 100 km seems reasonable given the paucity of Valais ophiolites in the Alps. Occurrences of Valais ophiolite are so few and small that the idea of a Valais basin floored by oceanic crust was long controversial (Trümpy, 1980), even until recently (Dal Piaz, 1999; Dercourt, 2002; Manatschal et al., 2006; Beltrando et al., 2007). In spite of this, we regard the geological and geochronological evidence for mantle exhumation accompanied by basaltic igneous activity and sea-floor spreading in the Valais basin as conclusive (Steinmann, 1994; Stampfli et al., 1998; Bousquet et al., 1998; Fügenschuh et al., 1999; Loprieno, 2001; Bousquet et al., 2002; Liati et al., 2003a), while admitting that not all sediments attributed to the Valaisan paleogeographic domain are floored by ophiolites (e.g., Fügenschuh et al., 1999). Zircons from lower crustal rocks exhumed during the rifting of the Valais Ocean often also yield Permian U–Pb ages (Froitzheim and Rubatto, 1998; Manatschal et al., 2006; Beltrando et al., 2007), suggesting that Late Cretaceous rifting and spreading localized along sites of previous Late Paleozoic (post-Variscan) magmatism and transtension (Schuster and Stüwe, 2008).

Breakaway and spreading of the Valais Ocean led to the individuation of the Briançonnais platform or continental fragment (Figs. 10 and 11; Stampfli, 1994), a narrow strip of thinned European continental lithosphere along the western part of the Alcapia


a
35 Ma
Priabonian
Anomaly 15
Europe
Valais Ocean
Piemont Ocean
W. Alpine Orogen
Eastern Alps
Periadriatic Fault
Dinaric Orogen
Bay of Biscay
Pyrenean Orogen
Iberia
E. Ligurian Ocean
Adria
Alkapeca
Atlantic Ocean
Ionian Sea
Africa
0 km 500
b
20 Ma
Aquitanian
Anomaly 6
Europe
Valais Ocean
W. Alpine Orogen
Eastern Alps
Periadriatic Fault
Dinaric Orogen
Bay of Biscay
Pyrenees
Iberia
N. Balearic Transform
Alkapeca
Apenninic Orogen
Adria
proto-Hellenic Arc
Atlantic Ocean
proto-Calabrian Arc
Ionian Sea
E. Mediterranean Sea
proto-Gibraltar Arc
Africa
0 km 500
Legend
Lithosphere
continental undeformed
oceanic
orogenic
Reference Pts.
a Galicia
b Corsica
Iberia
c Rabat
d Tunis
Africa
e Ivrea
Adria
present Ivrea
Major Faults
active
inactive
major thrust
normal
strike - slip

microplate that is presently exposed in the internal basement nappes of the Central and Western Alps (Fig. 4). The absence of Briançonnais basement nappes between Valaisan and Piemont–Liguria units in the Tauern Window of the Eastern Alps (Fig. 4) indicates that the Briançonnais platform tapered out to the east, where the Valais Ocean spread within the older Piemont Ocean (Channell and Kozur, 1997; Schmid et al., 2004a), most likely along the NW side of this ocean as depicted in Fig. 10.

We note that the estimated 100 km of E–W spreading of the Valais Ocean during the aforementioned 130–93 Ma time span is significantly less than the 520 km of sinistral transform motion of Iberia with respect to Europe over the same period (Fig. 10b). A corresponding discrepancy exists for the rates of Valais spreading (0.3 cm yr^{-1}) and Iberian transform motion (1.3 cm yr^{-1}, Fig. 16). These differences in amounts and rates of E–W motion between Europe, Iberia and Alcapia obviate a simple kinematic link between Valais Ocean spreading and Iberian counter-clockwise rotation; in fact, they require that the Alcapia microplate was decoupled from the Iberian microplate for the duration of Iberia's rotation, at least until Santonian time. We therefore propose that a single Cretaceous sinistral transform fault extended eastward from the Bay of Biscay and across Alpine Tethys to form the plate boundary between Alcapia and Iberia, where it merged laterally with the convergent boundary between Alcapia and the combined Adria/Africa plate (Fig. 10). This Cretaceous transform was therefore the site of two triple junctions: a transform–transform–ridge junction (Europe–Iberia–Alcapia) and a transform–trench–trench junction (Alcapia–Iberia–Africa). The rates and amounts of motion probably varied along the strike of this transform, as discussed below.

4.2.2. Eo-alpine Orogeny

The Eo-alpine Orogeny lasted from 140 to 84 Ma and affected all levels of the continental crust, as manifested by the three main rock complexes forming the edifice of the Eastern Alps today (Figs. 4 and 5): Deeply subducted and exhumed basement of the Koralpe-Wölz unit (location in Fig. 4, purple areas in Fig. 5), thin basement nappes often with greenschist- to amphibolite-facies metamorphism, and non-metamorphic cover nappes of the Northern Calcareous Alps that derived from the distal northern continental margin (Hallstatt) adjacent to Neotethys (Meliata–Maliac Ocean). The Northern Calcareous Alps (NCA) contain relics of the onset of continental accretion, including deep-water conglomerates (Rossfeld Formation in Fig. 6) with ophiolitic detritus (Faupl and Wagreich, 2000) that were deposited on the Hallstatt continental margin in Valanginian to Aptian time (140–125 Ma, e.g., Gawlick et al., 1999; Faupl and Wagreich, 2000). During Aptian time (125–112 Ma), this syn-orogenic sedimentation shifted progressively further to the northwest into units presently preserved in successively lower tectonic units of the NCA. Following Faupl and Wagreich (2000), we interpret this shift in sedimentation to mark the migration of the thrust front at the base of the advancing Eo-alpine orogenic wedge that, however, had not yet reached the Piemont Ocean by this stage. This thrust front formed the boundary of the Alcapia and the united Adria–African plates, as shown in Fig. 10. The orogenic wedge grew as the remaining part of lower-plate continental material (Alcapia) was progressively accreted to the upper continental plate (Adria–Africa) during NW-directed thrusting (blue arrows in Fig. 5). We note that the Eo-alpine orogenic wedge contained no suture in the classical sense of an ophiolite belt sandwiched between metamorphosed upper and lower-plate units. Instead, it incorporated continental units that were adjacent to Neotethys, including rare relics of the Meliata–Maliac Ocean found in Jurassic-age accretionary wedges (Mandl and Ondrejicka, 1991, 1993). These units that are preserved in the highest thrust sheets of the Northern Calcareous Alps were detached early on and hence largely escaped Cretaceous metamorphism (Fig. 5).

The occurrence of 100 Ma old, deep (>80 km) mantle-derived basanitic dykes within the western NCA (Fig. 6) indicates that detachment of the NCA nappes from their crustal and mantle underpinnings post-dated the dyke intrusions, with subcontinental mantle still present below this part of the NCA in Aptian time (Trommsdorff et al., 1990). This precludes the onset of active margin tectonics involving the subduction of Alpine Tethyan mantle lithosphere beneath the Alcapia continental margin before Aptian time as proposed by many authors (e.g., Winkler, 1988; see discussion below). Many thrusts in the NCA are sealed by Upper Turonian shallow-water "Gosau" clastics (Fig. 6). Taken together, these data indicate that the adjacent Piemont–Liguria Ocean was not subducted below the NCA at the front of the Austroalpine orogen before about 90 Ma.

The Eo-alpine Orogen was the site of intracontinental subduction and basement nappe stacking (Fig. 11b) whose direct traces can be found today in an E–W trending belt of Late Cretaceous, high-pressure and ultra-high pressure rocks (the Koralpe-Wölz unit, purple domains in Fig. 5, Thöni et al., 2008). The most reliable high-retentivity ages for the baric peak of this subduction-related metamorphism cluster in the range of 95–89 Ma, with mica-cooling ages constraining rapid exhumation (5–10 cm yr^{-1}) of these units into shallow levels of the orogenic wedge to have occurred at 89–84 Ma (Thöni, 2006, Fig. 13a). The protoliths of the HP and UHP rocks are Early Permian N-type (i.e., "normal") MORB rocks (Thöni and Jagoutz, 1992; Schuster and Thöni, 1996) that were probably intruded into a post-Variscan (Permian) intracontinental rift zone (Schuster and Stüwe, 2008). This structure was likely oriented ENE–WSW, parallel to identically aged basins across Europe (e.g., Ziegler, 1990; Burg et al., 1994), and was possibly continuous to the east with the Triassic–Jurassic embayment of a remnant part of the Meliata–Maliac Ocean in Fig. 8b. The dense, isostatically unstable rocks of this ancient intracontinental rift represented an obvious site for the Eo-alpine intracontinental subduction shown in Figs. 10b and 11b (Schmid et al., 2004a; Froitzheim et al., 2007; Stüwe and Schuster, 2010) that we propose was triggered by westward transform propagation of the subduction zone in the Meliata–Maliac Ocean. The exhumation and extrusion of this wedge of HP and UHP rocks was both to the N and W, as indicated by top-E to top-S transport directions of the hangingwall of normal faults above the Koralpe-Wölz unit (Fig. 5, references therein). These varied directions suggest that both subduction and exhumation were highly oblique (Thöni, 2006), consistent with the transpressive setting shown for the Eo-alpine Orogen in Fig. 10b. We note that our explanation of Eo-alpine intracontinental subduction triggered by pull of the Neotethyan oceanic slab (discussion in Section 6) differs from the idea of subduction initiated solely by gravitational sinking of negatively buoyant, Permian intrusive rocks (Stüwe and Schuster, 2010).

Thrusting affected progressively more external (i.e., northern and western) units of the orogenic crust, with near-surface thrusting manifested by Cenomanian–Turonian flysch (100–89 Ma, e.g., Roesli, 1944; Caron et al., 1982) and detachment in the basement leading to the stacking of thin nappe slices (1–2 km thick, Dal Piaz et al., 1972; Ratschbacher et al., 1989; Schuster et al., 2004) under greenschist- to amphibolite-facies metamorphic conditions (Thöni, 1986; Thöni and

Fig. 14. Plate tectonic maps for Alpine Tethys showing plate motions with respect to stable Europe during Cenozoic time: (a) 35 Ma, onset of Alpine collision inducing changes in subduction polarity immediately thereafter (see panel b); (b) 20 Ma, long after the change in subduction polarity S and W of present-day Liguria; Adria rotated counter-clockwise and indented the Alpine orogenic wedge; rollback subduction of the eastern Ligurian Ocean and formation of the Calabrian arc. Configuration for adopted and modified from Michard et al. (2006) except where discussed in text (e.g., Ionian Sea). Lines show traces of the cross sections in Fig. 15. City locations for reference on stable Europe: R = Rennes, W = Wien (Vienna), Z = Zürich.

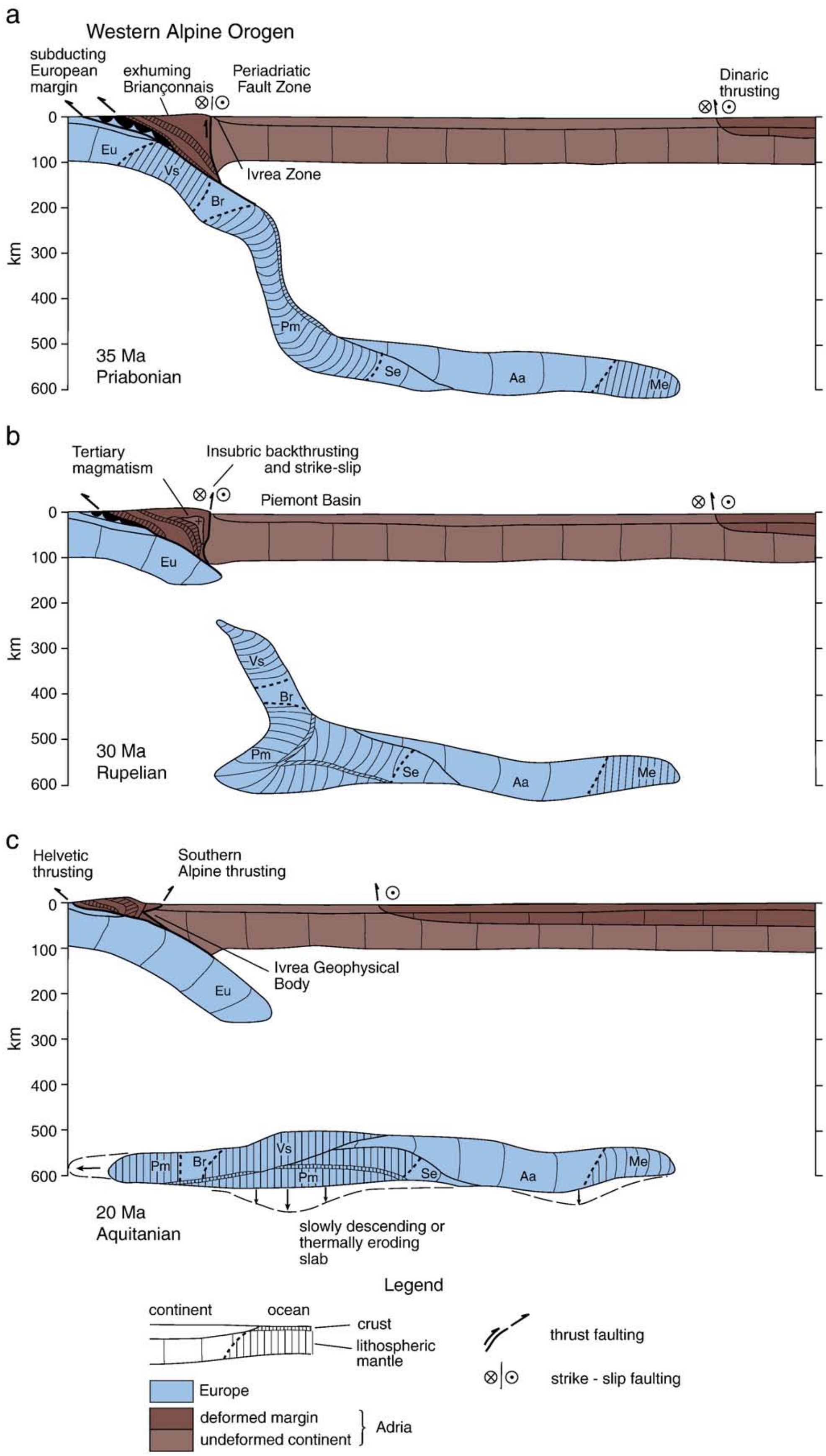


Fig. 15. Cross sections through Western Alpine Orogen and Adriatic plate with Dinaric thrusting: (a) 35 Ma, slab break-off and onset of collision in the Western Alps; (b) 30 Ma, Alpine collision and Adriatic indentation after slab break-off; (c) 20 Ma, late collisional backfolding of partly exhumed Early Cenozoic nappe edifice in the Western Alps. Location of cross sections shown in Fig. 14. Aa = Austroalpine (Alcapia) continental lithosphere, Br = Briançonnais continental fragment, Eu = distal European continental margin, Pm = Piemont oceanic lithosphere, Me = Meliata–Maliac oceanic lithosphere, Se = subducted part of Sesia continental lithosphere, Vs = Valais oceanic lithosphere.

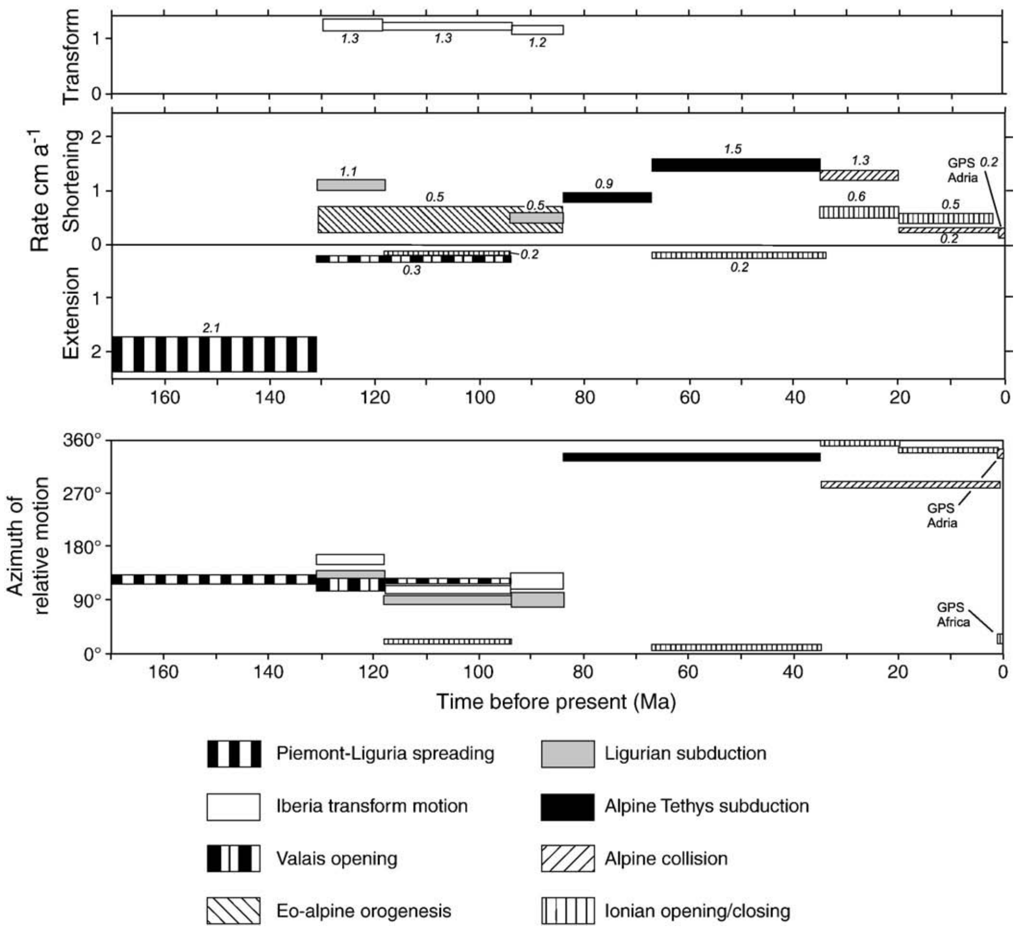


Fig. 16. Rates and directions of plate convergence and divergence in Alpine Tethys. The rates are calculated parallel to the motion paths of points a to e in Fig. 7. Width of the bars indicates error associated with uncertainties in timing and amount of displacement.
Present rates and directions of Adria with respect to Europe taken from Nocquet and Calais (2004) and Vrabec et al. (2006).

Miller, 1987). Lower crustal rocks are not exposed in these Austroalpine nappes, indicating that the lower continental crust was subducted together with its lithospheric mantle substratum in the down-going Austroalpine slab (Fig. 11b).

Basement thrusting in the Eastern Alps ended no later than 90–70 Ma as indicated by metamorphic isograds and mica-cooling isochrons that cross-cut thrust contacts (Oberhänsli et al., 2004). Thrust contacts in the Austroalpine basement nappes and the Northern Calcareous Alps were sealed by syn- to post-orogenic clastic sediments in formations of the “Gosau” Group (Fig. 4; e.g., Ortner, 1994; Eisbacher and Brandner, 1996; Ortner, 2001), some of them deposited in intra-orogenic extensional basins (Fig. 13a). Like the thrusting before, extensional tectonics generally migrated from SE to NW (Ratschbacher et al., 1989), beginning at 94 Ma in units presently exposed east of the Tauern window (Fig. 4) and reaching units at the western border of the Eastern Alps at about 84–80 Ma (Handy et al., 1993; Froitzheim et al., 1994; Handy et al., 1996). The depth of these basins increased markedly with time, with initial fluvial and shallow-marine sedimentation in normal-fault bounded basins (Lower Gosau subgroup, e.g., Wagreich, 1995) passing up-section into pelagic and turbiditic sedimentation in both dextral and sinistral pull-apart basins (Upper Gosau subgroup, Neubauer et al., 1995). The boundary between these subgroups is diachronous (Fig. 6), with older ages in the east (late Turonian–Santonian, 90–84 Ma) than in the west (Maastrichtian, 71–65 Ma, Wagreich, 1995). Considered in the context of plate dynamics, the first “Gosau” extensional phase may reflect thinning of the orogenic lithosphere during overall NW-propagation of the subducting slab (Fig. 13a), whereas the second “Gosau” extensional phase may be attributed to further thinning and pronounced subsidence triggered by active margin tectonics involving the subduction of Piemont–Liguria oceanic lithosphere during subsequent northward motions of Africa and Adria described below (Section 4.3). The relief at that time was probably subdued and only locally emergent (Oberhauser, 1995) as predicted by dynamic topographic models of subduction (Husson, 2006).

The Southern Alpine units formed an effective backstop to the Eo-alpine orogenic wedge, as they are largely unaffected by Alpine metamorphism (Fig. 5) and underwent only S-directed brittle folding and thrusting during Late Cretaceous and mostly during Cenozoic time (Fig. 6, Schönborn, 1992). The rigid lithosphere of the Southern Alps must therefore have remained decoupled from the orogenic lithosphere of the Eastern Alps by a Late Cretaceous precursor to the Periadriatic fault system. Also the distal parts of the Adriatic continental margin lithosphere presently exposed in the Western Alps (the Sesia Zone, Fig. 4) were not affected by Eo-alpine thrusting and metamorphism. The lack of Late Cretaceous (110–90 Ma) HP and UHP metamorphism in the Western Alps compared to the Eastern Alps (Fig. 5) suggests that the Eo-alpine Orogen did not extend into the Western Alps, but was bounded to the west by top-W thrusts (Fig. 10b; e.g., Handy et al., 1993; Froitzheim et al., 1994; Handy, 1996; Handy et al., 1996). The amount of shortening is very poorly constrained at present, but probably did not significantly exceed the amount recorded by E–W shortening within the Austroalpine basement nappes (≥100–150 km, Manatschal and Bernoulli, 1999).

We note that although the Late Cretaceous precursor of the Periadriatic fault juxtaposed Eastern and Southern Alpine lithospheres with contrasting thermo-mechanical properties, it was not a microplate boundary in the sense of Boullin et al. (1986) and Michard et al. (2002), who proposed that it delimited the Adriatic plate in the south from the Alkapeca or Alboran–Sesia–Margna microcontinent in the north. Instead, we envisage that the Eo-alpine Orogen comprised parts of the Alcapia microplate that were accreted to the base and leading edge of the overriding Adriatic microplate in Late Cretaceous time, as shown in Fig. 10b.

The complex configuration of microplate triple junctions at 94 Ma in Fig. 10b reflects the kinematic necessity of accommodating faster eastward motion of the Iberian microplate than the Adriatic microplate that also moved eastward with respect to Europe, but at a lower rate (Fig. 16). Though speculative, this configuration explains anomalous W- to SW-directed Late Cretaceous nappe stacking under pressure-dominated, greenschist-facies conditions along the western border (Err unit in Figs. 4 and 5; Ring et al., 1989; Liniger and Nievergelt, 1990; Froitzheim et al., 1994; Handy, 1996; Handy et al., 1996), i.e., perpendicular to the predominant N- to NW-directed transport directions for all other parts of the Eastern Alps (Fig. 5). Subduction of the Piemont Ocean along this western margin started somewhat earlier than along the northern front (Figs. 10b and 11b) as indicated by the Late Turonian to early Coniacian (89–88 Ma) age of deep-water conglomerates and wildflysch of the Arosa Zone (Fig. 4; Oberhauser, 1983; Winkler and Bernoulli, 1986; Winkler, 1988).

4.2.3. Partial subduction of the Ligurian Ocean

Twice during the early Late Cretaceous, the Iberian plate converged with the Adriatic microplate (Fig. 10a,b) in an E–W direction according to the plate-motion paths in Fig. 7: between 131 and 118 Ma by some 137 km, and again between 94 and 84 Ma by an estimated 50 km. These amounts are modest, but we recall that they are minimum values and may be much greater depending on the amount of Late Cretaceous to Early Cenozoic shortening obtained from retrodeformation of the Alps. We propose that these two phases of Late Cretaceous east–west convergence were accommodated by E-directed subduction of parts of the Ligurian Ocean and that the fragment of Alkapeca continental lithosphere separating the eastern and western branches of the Ligurian Ocean (Fig. 10) played a key role in determining the locus of this subduction. The kinematic necessity of accommodating the first stage of east–west convergence between points b and e on Iberia and Adria, respectively, plus the lack of direct evidence so far for early Late Cretaceous subduction in Alpine Corsica leads to us to argue that intra-oceanic subduction of a part of the eastern Ligurian Ocean is the only viable solution (Fig. 10a). This intra-oceanic subduction continued until the eastern margin of the Alkapeca continental fragment entered the subduction zone (Fig. 10a). Subduction then jumped to the western Ligurian Ocean (Fig. 10b), leaving part of the Alkapeca continental fragment intact and a broad expanse of the eastern Ligurian Ocean still open. It is important to emphasize that most of the eastern branch of the Ligurian Ocean was consumed much later during Oligo-Miocene rollback of the Calabrian arc–trench system as discussed below in Section 4.4.2.

Late Cretaceous subduction of the western branch of the Ligurian Ocean and part of the western continental margin of the Alkapeca continental fragment (Figs. 10b and 12a) is documented by 84 Ma eclogite-facies metamorphism in imbricated ophiolitic and continentally derived rocks on Corsica (Morteda-Farinole unit, Dal Piaz and Zirpoli, 1979; Sm–Nd mineral isochron of Lahondère and Guerrot, 1997) as well as detrital glaucophane in Maastrichtian (71–66 Ma) sediments of eastern Sardinia (Dieni and Massari, 1982). The late Santonian age for this HP metamorphism requires that subduction of parts of the western Ligurian Ocean began already 10 Ma earlier, at about 94 Ma, for the rocks of the ocean–continent transition to attain the geobarometrically constrained depth of subduction (50 km) at the average 0.5 cm yr^{-1} rate of convergence between Iberia and Adria for this time (Fig. 16). This subduction was generally E-directed according to the motion paths of Iberia and Adria in Fig. 7, although thrusting of western Ligurian ophiolite-bearing nappes on Corsica was NW-directed as indicated by the average azimuth of stretching lineations on Corsica in its pre-late Oligocene orientation (Fig. 5). Subduction eventually also affected the Iberian continental margin in Eocene time according to Ar–Ar phengitic mica ages (Brunet et al., 2000) and lasted until Bartonian time (40–37 Ma) when fossiliferous sediments lacking HP mineral assemblages were deposited unconformably on basement rock, thereby sealing the previously subducted and exhumed Corsican nappe stack (Egal, 1992; Caron, 1994). The base of this nappe stack comprises units of the Iberian continental margin that include autochthonous, early Mid-Eocene sediments (Bezert and Caby, 1988) which were affected first by 39–32 Ma HP metamorphism, then by cooling and exhumation ending at about 25 Ma (e.g., Brunet et al., 2000). This constrains rapid exhumation following subduction to have ended no later than early Oligocene time, similar to the evolution of European-derived units with HP metamorphism in the main body of the Alps, discussed below in Section 4.3. We note that Malavieille et al. (1998) also proposed intra-oceanic subduction of the Ligurian Ocean beginning in Cretaceous time, but thought the continental protoliths of the Late Cretaceous eclogites on Corsica to be derived from the distal Iberian margin (lower, subducting plate) rather than from the eastern distal margin of the Alkapeca continental fragment (upper plate), as in our reconstruction. The provenance of these protoliths is indeed debateable, but we favour an origin from Alkapeca because of their structural position in the Corsican nappe pile above Early Cenozoic HP units and their HP age that is significantly older than the late Early Cenozoic HP ages in units of European affinity (e.g., Berger and Bousquet, 2008). The similarity of these and other related continental protoliths in the Corsican nappe pile (mostly Permian granite and gabbroic granulite) with rocks presently exposed on Calabria supports the arguments advanced by Michard et al. (2002) and reinforced by Molli (2008) in favour of the Alkapeca continental fragment that originally lay to the east of Corsica and separated eastern and western branches of the Ligurian Ocean.

Throughout early Late Cretaceous time, the partial subduction of the Ligurian Ocean was linked to the northeast with the Eo-alpine Orogen along a segmented trench-to-orogenic front system, depicted in Fig. 10. The Eo-alpine thrust front did not reach the Austroalpine continental margin with the Piemont–Liguria Ocean (Fig. 10) until about Santonian time (Fig. 12a) as documented by the onset of abundant flysch sedimentation associated with SE-directed subduction of the Piemont part of Alpine Tethys, further discussed below in Section 4.3. Older turbiditic sequences from this margin (Upper Aptian–Lower Cenomanian flysch of the so-called "Randcenoman Schuppe", e.g., von Eynatten and Gaupp, 1999; Auer and Eisbacher, 2003, and of the "Aroser Schuppenzone", Winkler and Bernoulli, 1986; Winkler, 1988) with mixed components of continental (Austroalpine) and oceanic (mostly Meliata–Maliac) origin betray a pronounced submarine relief in originally elongate basins (Faupl and Wagreich, 2000; Wagreich, 2001) located well north of the advancing orogenic front at that time. Past workers have attributed this relief to early transpression (Gaupp, 1982) or even subduction (Winkler, 1988; Oberhauser, 1995; Winkler et al., 1997), but we find such scenarios unlikely given that the components in these sediments probably derived partly, if not entirely, from the far-travelled nappes of the NCA which contain transported fragments of Neotethys (Meliata–Maliac Ocean). These fragments of Triassic and Jurassic ophiolites came from the other (eastern) side of the Adriatic microplate and were therefore unrelated to the subduction of the Piemont Ocean.

The western continental margin of Adria is interpreted to have remained passive throughout Late Cretaceous and early Cenozoic time (Figs. 12 and 14a) despite the widespread occurrence of olistostromes containing ophiolitic blocks (referred to as "basal complexes") that underlie Late Cretaceous to Eocene clastic or calcareous flysch sequences in the Western Alps and the Apennines. The age of the olistostromes in the basal complexes ranges from Late Cenomanian to Santonian in units of the "Nappe Supérieure" or Simme nappe s.l. of the Préalpes (location in Fig. 4; "complexe de base", Caron et al., 1989; Bill et al., 1997) and Santonian to Campanian in the Apennines ("complesso di base", Marroni et al., 2001). These olistostromes are testimony to a submarine topography that must have existed in Late Cretaceous time at the transition to the eastern Ligurian Ocean. Although we cannot exclude some late Cretaceous strike-slip motion along this ocean–continent transition, these basal complexes and their Late Cretaceous to Late Eocene sedimentary cover (e.g., Marroni et al., 2001) were not involved in orogeny before latest Eocene times.

4.2.4. Widening of the Ionian Sea

Between 118 and 94 Ma and again between 67 and 35 Ma, the Adriatic microplate rotated counter-clockwise and moved away from Africa, leading to slow widening (0.2 cm yr^{-1}) of the Ionian Sea (Figs. 10b, 15a, and 16). According to our reconstruction, this oceanic domain already existed by the Early Jurassic (Fig. 8a) and quite possibly developed earlier in connection with the opening of the eastern Mediterranean in Early Mesozoic time (Catalano et al., 2001). The age of the Ionian Sea is perhaps the most poorly constrained of all oceanic domains in the Mediterranean due to the great thickness of Messinian salt deposits that hinders drilling and borehole stratigraphy down to the basement and older sediments in this area. Catalano et al. (2001, 2002) argue that rifting began in pre-Late Triassic time, but note that normal faults dissect Late Jurassic–Early Cretaceous pelagic deposits, indicating later extension. These authors infer very slow spreading (<1 cm yr^{-1}) of the Ionian Sea in Late Jurassic to Early Cretaceous time based on its thick lithosphere (90 km), low heat flow (34 mW m^{-2}) and smooth, deep abyssal plain (>4000 m). These inferences and observations are broadly consistent with our reconstructions, but we hasten to point out that the location and width of the Ionian Sea in our maps is determined solely by the gap between Sicily and the Apulian peninsula (the heel of southern Italy in all maps); this gap varies through time as a function of the backrotations and retrotranslations of Adria with respect to Africa around the Ivrea pole.

4.3. Late Cretaceous to Early Cenozoic northward motions of Adria and Africa and the subduction of Alpine Tethys

Important plate reorganization took place sometime between Cenomanian (Fig. 10b) and Santonian (Fig. 12a) times, when the Adriatic microplate re-united with the African plate to become a promontory of Africa (Argand, 1924; Channell and Horvath, 1976). This composite plate included the still open part of the eastern branch of the Ligurian Ocean and the Alkapeca continental fragment. The NNW motion of this composite plate with respect to the united Iberia–Europe plate was maintained throughout the Late Cretaceous (Fig. 12) until collision in Late Eocene time (Fig. 14a). The Adriatic promontory was bounded by a single active margin that involved SE-directed subduction of the Piemont Ocean and the western branch of the Ligurian Ocean, extending some 2000 km all the way from the Eastern Alps to the Betic Cordillera in southern Spain. The uniform subduction direction is mirrored both by the sequence of nappe stacking (European-derived units on bottom) and by the consistent top-N to -NW sense of shear in latest Cretaceous to Early Cenozoic HP units, from the Alps (green arrows in Fig. 5) to the Betic Cordillera (e.g., Michard et al., 2002, 2006). A similarly continuous Alpine subduction zone was already proposed by Michard et al. (2002) and Molli (2008) based on earlier ideas of Elter and Pertusati (1973).

The age of the onset of active margin tectonics at the northern edge of the Adria–Africa plate probably varied along strike, primarily because the NW convergence direction was at 60–70° angles to the irregular transform structures inherited from E–W-directed rifting and spreading of Alpine Tethys. However, using the conservative criteria in Section 3.3 for dating accretionary thrusting, we find that active margin tectonics began in Santonian time, both in the Alps proper as well as in the part of the Alps that were later incorporated into the northern Apennines (Elter and Pertusati, 1973). This is consistent with the earliest age of eclogite-facies metamorphism on Corsica (84 Ma, Lahondère and Guerrot, 1997), as well as the first stage of subduction in the Betic Cordillera beginning in Cretaceous time (see compilation of radiometric ages in Puga et al., 2009, their Table 2). The cross sections in Figs. 13 and 15 are oriented sub-parallel to the 84–35 Ma subduction direction and show how the lithosphere of Alpine Tethys, now part of the down-going European plate, became part of the already long slab which had reached the top of the mantle transition zone by 84 Ma.

4.3.1. Subduction erosion at the NW tip of the Adriatic promontory

The trench along the active Alpine margin is inferred to have skirted the NW tip of the Adriatic promontory in the vicinity of the continental Sesia and Canavese Zones (Figs. 10b and 12a). This part of the active margin was anomalous because a corner of upper Adriatic plate represented by the Sesia Zone was tectonically eroded and subducted to 60–65 km depth already by 75–65 Ma (Fig. 13b; Duchêne et al., 1997; Rubatto et al., 1999; Konrad-Schmolke et al., 2006), then exhumed to 10–15 km depth within the nascent Western Alpine accretionary wedge by 63 Ma, just before or at the onset of ocean subduction in this part of Alpine Tethys in Paleocene–Eocene time (Babist et al., 2006). Subduction erosion was favoured by the unusual circumstance that the Sesia Zone comprised one or more extensional allochthons situated at the most distal part of the Early Mesozoic passive margin of Adria (Schmid, 1993; Froitzheim et al., 1996; Babist et al., 2006) and was separated from the more proximal parts of this margin by thinner continental crust of the Canavese Zone (Biino et al., 1988; Ferrando et al., 2004). Moreover, the lithosphere comprised Early Permian mafic lower crust and upper mantle rock similar to that presently exposed in the Ivrea Zone (Handy and Zingg, 1991), possibly rendering it negatively buoyant and thus susceptible for subduction. These factors may also explain why an adjacent piece of lithospheric mantle (the Lanzo Zone in Fig. 4) from the ocean–continent transition in the same area remained subducted for 10 My (55–45 Ma according to Müntener et al., 2007).

We emphasize that the Sesia Zone in the Western Alps (Fig. 4) was never part of the Austroalpine nappe system in the sense that the Sesia extensional allochthon was subducted and incorporated into the latest Cretaceous accretionary prism (Fig. 13b), whereas the "true" Austroalpine nappes further to the NE in the Eastern Alps formed the upper plate of the active plate margin (as depicted in Fig. 13a for an earlier time slice). In the transect of Fig. 13b, the Ivrea Zone at the edge of the Adriatic microplate constitutes the upper plate during subduction of the Piemont Ocean. Even further to the SW, the upper plate consisted of the Alkapeca continental fragment and the not-yet subducted eastern branch of the Ligurian Ocean (Figs. 12a and b). A relic of this upper plate oceanic lithosphere is well preserved in the non-metamorphic Chenaillet unit of the Western Alps, which overlies Piemont oceanic crust with a high-pressure metamorphic overprint (Schwartz et al., 2007). This scenario accounts for some of the major differences between Eastern and Western Alps (recall discussion in the Chapter 1) that are often overlooked by adherents of cylindrism in the Alps.

4.3.2. Rotation of Adria and accelerated subduction of Alpine Tethys

Beginning sometime between 67 and 56 Ma, the convergence rate between Europe and Adria increased from 0.9 to 1.5 cm yr^{-1} and maintained the latter rate until subduction ended at about 35 Ma (Fig. 16). This coincided with counter-clockwise rotation and NW translation of Adria with respect to both Europe and Africa (Table 1) that was accommodated by renewed spreading of the Ionian Sea (Fig. 12b) and possibly also rifting in the Sirte Basin east of Tunis (Fig. 12b, see Capitanio et al., 2009 for a different interpretation of the origin of the Sirte Basin).

The progressive subduction of Alpine Tethys in Early Cenozoic time and the evolution of the Western Alpine accretionary wedge above the descending European slab are shown in four cross sections, beginning with subduction of the Piemont Ocean (Figs. 13a and b) and the Briançonnais continental fragment (Fig. 13c), and ending with subduction of the Valais Ocean and the distal European margin (Fig. 15a). The best record of in-sequence thrusting of Alpine Tethyan sediments that entered the subduction zone is preserved in the imbricated cover nappes of the Préalpes and related klippen of the Central Alps (Fig. 4; Trümpy, 2006); these nappes were progressively detached from the down-going oceanic and continental crust early in the accretionary history and thus experienced only weak or no metamorphism when they were incorporated into the Western Alpine accretionary complex (Stampfli et al., 1998 and references therein), well before their final emplacement onto the European margin in late Miocene time (Trümpy, 1980). Subduction of the Piemont Ocean began in the Paleocene (Schmid et al., 1996), except for those parts that had already been subducted and exhumed with the adjacent Sesia zone in Late Cretaceous time. The uninterrupted deposition of early to middle Eocene (Ypresian–Lutetian) flysch marked the continuous arrival of oceanic crust at the trench from 56 to 40 Ma (Trümpy, 1980; Matter et al., 1980; Stampfli et al., 1998; Trümpy, 2006).

Further to the SW, in an area corresponding to the eastern Betic Cordillera, early Cenozoic subduction of the western Ligurian Ocean was SE-directed and involved top-NW thrusting of the encroaching Alkapeca margin (Alpujarrides unit, including exhumed peridotites) onto transitional Iberian-western Ligurian lithosphere (ophiolite-bearing Mulhacen Complex of the Nevado-Filabride Complex, Trommsdorff et al., 1998; Puga et al., 2009) and finally onto the Iberian continental margin (radiometric age data in Puga et al., 2009, their Table 2). The frontal thrusts at the tip of the Alkapeca units (Malaguides) were eventually sealed by Upper Oligocene conglomerates (Lonergan, 1993).

The Briançonnais continental fragment was subducted somewhat later than the Piemont Ocean, starting in late Paleocene time in Eastern Switzerland (Schmid et al., 1996); Middle Eocene (Lutetian) flysch marks the incorporation of Briançonnais crust into the toe of the accretionary prism at 49–40 Ma (Fig. 13c, Stampfli et al., 1998). The predominance of older flysch ages in eastern parts of the Briançonnais suggests that subduction of the Briançonnais continental fragment may have been diachronous, possibly beginning in the eastern Briançonnais during late Paleocene time and migrating towards the Western Alps. Subduction of the Briançonnais continental fragment was immediately followed by the accretion and subduction of Valais oceanic lithosphere (Fig. 15a) leading to the formation of the narrow, external blueschist-facies belt that today extends from the Tauern and Engadin Windows in the east all the way to the Western Alps (Fig. 5, Bousquet et al., 2008; Wiederkehr et al., 2008). Finally, accretion of the European passive margin at the toe of the subduction zone is documented by Priabonian mélange (37–34 Ma) in Ultrahelvetic imbricate slices (Matter et al., 1980).

The record of Cenozoic subduction metamorphism in the core of the Western Alps (blue areas in Fig. 5, Goffé et al., 2004; Oberhänsli et al., 2004) is broadly consistent with the SE to NW younging of flysch ages (Fig. 6, review of Berger and Bousquet, 2008): High-retentivity ages of HP and UHP assemblages from Piemont–Liguria units range from 51 to 40 Ma and overlap with the younger ranges of HP and UHP ages from Briançonnais-derived units (47–43 Ma). The peak of high-pressure metamorphism in the Valais-derived units was recently dated at 42–40 Ma (Wiederkehr et al., 2009) and in the Europe-derived units at 41–35 Ma (Berger and Bousquet, 2008 and references therein). Jolivet et al. (2003) noted that the peak pressures and temperatures of the HP metamorphism in these different units define a common line in a pressure–temperature diagram (see their Fig. 14). If valid, this linear P–T relationship may support the idea that subduction and exhumation occurred along a single, Early Cenozoic slab subducting at a constant rate and angle (Gueydan et al., 2009), rather than several smaller slabs that underwent piecemeal subduction at fluctuating rates as proposed by Rosenbaum et al. (2002a).

Exhumation of the HP and UHP units in the Western Alps migrated rapidly from SE to NW behind the subduction zone (Wheeler et al., 2001), as indicated by the younging of mica-cooling ages from 60 Ma in the Sesia Zone towards ages of about 35 Ma in the Piemont–Liguria, Briançonnais and Valais units of the Western Alps (Berger and Bousquet, 2008). There, zircon fission-track ages ranging from 35 to 30 Ma mark the end of rapid decompression and exhumation (Malusa et al., 2005; Vernon et al., 2008). The rate of exhumation is calculated to have been 1 cm yr^{-1} or less by most authors (e.g., Rubatto and Hermann, 2006). Note that the remarkably high exhumation rate of 3–4 cm yr^{-1} previously proposed by Rubatto and Hermann (2001) for the UHP rocks of the Briançonnais-derived Dora Maira unit (Fig. 4, Chopin et al., 1991; Schertl et al., 1991; Tilton et al., 1991; Compagnoni et al., 1995) is based on unrealistically young radiometric ages for the baric peak of UHP metamorphism (35 Ma) and exhumation of this unit to low pressures (32 Ma); not only do these ages overlap with the aforementioned 35–30 Ma range of zircon fission-track ages, they are much younger than peak-pressure and decompression ages of other Briançonnais-derived units (Ambin, Gran Paradiso, Mt. Rosa units; Berger and Bousquet, 2008). Moreover, Upper Eocene to Lower Oligocene sediments of the Tertiary Piemont Basin (e.g., Laubscher et al., 1992) unconformably overlie HP ophiolitic units of the Ligurian Alps (Voltri area in Fig. 4) and seal the Early Cenozoic retro-wedge of the Western Alps (Barbieri et al., 2003). These data constrain most exhumation of the Cenozoic HP units to have occurred before 35 Ma. Similarly, the high erosion rate of 1 cm yr^{-1} calculated by Morag et al. (2008) is based on an unrealistically young age of peak pressure (34 Ma!) preserved in pebbles that arrived in the Alpine foreland at 32–30 Ma. Exhumation of the Briançonnais-derived units in the Western Alps involved no normal faulting in their hangingwall nappe contacts (Bucher et al., 2003, 2004; Bucher and Bousquet, 2007) and occurred at rates that not only are compatible with average erosion rates measured in mountainous areas worldwide ($\leq$1 cm yr^{-1} for catchment areas $\geq 10^4$ km^2, Burbank, 2002), but that did not exceed the Early Cenozoic plate-convergence rate in the Western Alps (1.5 cm yr^{-1}, Fig. 16). Eclogitic units in the Central Alps and Tauern Window that derive from the subducted European margin underwent substantial exhumation no later than 32 Ma, i.e., somewhat later than in the Western Alps, and prior to post-collisional Bergell magmatism (location in Fig. 4, Schmid et al., 1996 based on the 32 Ma intrusive age of von Blanckenburg, 1992) and re-heating in the Tauern Window (Kurz et al., 2008).

Regarding the Eastern Alps, the Austroalpine nappes at the leading edge of the advancing Adriatic promontory underwent a change from the second phase of "Gosau" extension ending at 50 Ma (Wagreich, 1995; Neubauer et al., 1995) to N–S thickening as they were further thrust at least 75 km (Milnes, 1978; Froitzheim et al., 1994) onto Paleocene–Eocene flysch of the subducting Valais and European margin lithospheres (Fig. 14a). This late Eocene to early Oligocene shortening of the Eastern Alps is manifested by N- to NNE-directed thrusting and folding under subgreenschist-facies conditions (red arrows in Fig. 5, "Blaisun phase" of Handy et al., 1993; Froitzheim et al., 1994; Handy et al., 1996), except immediately north of the Periadriatic fault system where folding and shearing under greenschist-facies conditions indicate greater crustal thickening (e.g., Liniger and Nievergelt, 1990).

The NNW motion and counter-clockwise rotation of Adria with respect to Europe between 67 and 35 Ma coincided with spreading in the Ionian Sea (Fig. 14a), as also shown in the reconstructions of Michard et al. (2002, their Fig. 5B, C) and Carmignani et al. (2004). Spreading was very slow (0.2 cm yr^{-1}, Fig. 16) and pre-empted any distributed extension of the Adriatic microplate above the SE-dipping European slab along its northern and western perimeter. Extension of the Adriatic microplate involved only minor normal faulting (imaged beneath the Po Plain southwest of Milan, Di Giulio et al., 2001) and limited Early Cenozoic, intraplate magmatism in the Veneto region (Macera et al., 2003; location in Fig. 4). The oldest intrusives in the southern part of the Adamello batholith (Fig. 4) may also be related to minor upper plate extension (42 Ma U–Pb single zircon ages, Mayer et al., 2003). We note that the thinned lower crust and mantle rocks of the Ivrea Zone (Fig. 4) are unrelated to Cenozoic extension, having been exhumed much earlier during E–W-directed Jurassic rifting of the Adriatic continental margin (e.g., Zingg et al., 1990; Handy and Zingg, 1991).

4.4. Adria–Europe collision and Ligurian rollback subduction following a change in subduction polarity

The end of Eocene time (35 Ma) witnessed dramatic changes in the motion and configuration of the independently moving Adriatic microplate. Note that Fig. 14a depicts the plate configuration immediately before this change, which began with the collision of Adria including the not-yet subducted parts of the eastern Liguria Ocean, with the European continental margin. Shortly thereafter, at around 30 Ma (Rosenbaum et al., 2002b; Faccenna et al., 2004) the remaining eastern part of the Ligurian Ocean began to subduct to the west beneath Europe–Iberia, which led to massive extension and opening of the Western Mediterranean Ocean due to rollback of the eastern Ligurian slab (Fig. 14b). Following Michard et al. (2002, 2006) and Elter et al. (2003), we advocate a change of subduction polarity from SE- to NW-directed along the entire length of the Ligurian domain. This change may have been triggered by a combination of continental collision in the Alps (Rosenbaum et al., 2002b) and collision of the Alkapeca continental fragment with the Iberian margin.

This eastern Ligurian subduction retreated rapidly to the S and SE before impinging with the African continental margin at around 17 Ma (Rosenbaum et al., 2002b; Faccenna et al., 2004). Today, the main vestiges of this subduction system are the dying Gibraltar arc and Calabrian arc–trench system (Fig. 1). In the vicinity of the Alps, this evolution entailed switches in subduction polarity at both ends (Fig. 14b), i.e., not only at the transition of the Western Alps to the northern Apennines (Vignaroli et al., 2008; Molli, 2008), but also at the Eastern Alps–Dinarides junction (Kissling et al., 2006; Ustaszewski et al., 2008). In the following, we focus on plate interactions up to 20 Ma, as the complex dynamics of Miocene and younger plate motions in the rest of the Western Mediterranean area are beyond the scope of this paper and have been treated elsewhere (e.g., Malinverno and Ryan, 1986; Royden, 1993; Doglioni et al., 1997, 1999; Michard et al., 2002; Rosenbaum et al., 2002b; Jolivet et al., 2003; Faccenna et al., 2004; Carmignani et al., 2004; Cavazza et al., 2004; Michard et al., 2006).

4.4.1. Collision in the Alps

The entry of buoyant European continental margin into the subduction zone in Priabonian time (Figs. 14a and 15a) was associated with only a slight decrease of the Adria-Europe convergence rate (1.5 to 1.3 cm yr^{-1} or less), but a marked change in convergence direction from NW–SE to WNW–ESE (Figs. 7 and 16). Thus, post-35 Ma shortening involved WNW-directed thrusting in the Western Alps associated with ESE-directed subduction of the European continental margin along the N–S-trending part of the Western Alpine arc (Fig. 3a), while the N–S component of convergence in the Central and Eastern Alps decreased to about 0.5 cm yr^{-1} (Dewey et al., 1989; Schmid et al., 1996).

The arc of the Western Alps also started to form at about 35 Ma (Schmid and Kissling, 2000; Ceriani et al., 2001) when the leading edge of the Adriatic microplate, with its cold and rigid upper mantle rocks of exhumed Jurassic continental margin (Ivrea Zone in Fig. 4), ploughed into the warm, partly exhumed Early Cenozoic nappes comprising slivers of Alpine Tethys and the European margin (Figs. 14b, 15b, and 15c). These originally Adriatic subcontinental mantle rocks correspond to the Ivrea Geophysical Body presently imaged beneath the internal part of the Central and Western Alps (e.g., Giese et al., 1982; Kissling, 1984). During middle Miocene rollback of the eastern Ligurian slab, SE-directed thrusting affected the external southwestern part of the arc of the Western Alps (Trullenque, 2005; Ford et al., 2006), and together with counter-clockwise rotations of the Ligurian Alps (e.g., Collombet et al., 2002), this finally led to the radial pattern of thrusting in the Western Alps (red arrows in Fig. 5). The ESE-dipping lithospheric slab beneath the Western Alps (Fig. 15c) continued to lengthen until late Miocene time, when it began to break off, possibly triggered by the further dramatic decrease in WNW–ESE convergence rate from 1.3 to only 0.2 cm yr^{-1} (Fig. 16). This partially severed European slab is visible today as a discontinuous, positive P-wave anomaly in tomograms across the arc of the Western Alps (Fig. 3a, Lippitsch et al., 2003; Kissling et al., 2006).

Prior to 35 Ma, the rest of the Alps was separated from the European foreland of the future Western Alpine arc by a N–S- to NNE–SSW-trending, sinistrally transpressive plate boundary (Fig. 14a; Ricou and Siddans, 1986; Schmid and Kissling, 2000; Ford et al., 2006). This oblique-sinistral motion probably initiated at 67 Ma or even earlier in order to accommodate Late Cretaceous–Early Cenozoic northward motion of Adria with respect to the united Iberia–European plate. Unfortunately, direct evidence for such a fault is lacking in the Western Alps due to overprinting during post-35 Ma arc formation. In the Alps east of this sinistrally transpressive plate boundary, the oceanic part of the European slab had reached the mantle transition zone already long before 35 Ma (Figs. 13b, 13c and 15a). We therefore propose that the negative buoyancy of this oceanic slab coupled with the change in Europe–Adria convergence direction at 35 Ma led to its steepening and thinning and eventually to its tearing beneath the eastern and central parts of the Alps (Figs. 15a and b) in a fashion similar to that previously proposed by von Blanckenburg and Davies (1995) and Kissling (2008). The completely detached part of the slab beneath the Central and Eastern Alps presently resides in the mantle transition zone (Anomaly A in Fig. 3b). We point out that the formation of the relatively short slab presently imaged by tomography in direct continuity with the orogenic crust beneath the Central Alps (Lippitsch et al., 2003, not shown in Fig. 3) and Eastern Alps (labelled Eu in Figs. 3b and d) is interpreted to comprise continental lithosphere (Kissling, 2008) that was subducted after the slab break-off event, because its 160 km length corresponds roughly to the amount of post-Eocene N–S crustal shortening in the Alpine nappe stack (Schmid et al., 2004a).

The origin of the relatively young slabs labelled Eu in Fig. 3b and d, the slab beneath the Western Alps (Fig. 3a), and a NE-dipping slab below the Eastern Alps (Lippitsch et al., 2003; Ustaszewski et al., 2008) is currently being debated. In any case, their present geometry is difficult to reconcile with uniform S- to SE-directed collisional subduction of European continental lithosphere along the entire length of the Alpine chain (Kissling et al., 2006). The NE-dipping slab beneath the eastern part of the Eastern Alps probably represents part of the Adriatic lithosphere that was inserted sideways from the SE, i.e. from the Dinarides, during Miocene-to-Recent counter-clockwise rotation and oblique subduction of the Adriatic microplate beneath Europe in the external Dinarides and the eastern part of the Southern Alps (Ustaszewski et al., 2008). This lateral insertion would have been made possible by lateral eastward propagation of the tear in the European slab into the Carpathian arc (Wortel and Spakman, 2000). The complex post-Oligocene tectonics in this area are another hot topic that lies beyond the scope of this paper and are only touched upon again briefly in Section 5 where we discuss the origin of subducted Alpine Tethyan lithosphere imaged by tomography.

The age and direction of propagation of slab-break off beneath the different parts of the Alps are also controversial. Estimates for the break-off time in the central part of the Alps vary with the criteria used: 45–40 Ma (retrodeformation of Early Cenozoic nappes, Schmid et al., 1996; time-lag between slab-break-off and 33–30 Ma magmatism along the Periadriatic fault system, von Blanckenburg and Davies, 1995), 35–25 Ma (plate motion and seismic tomography, Piromallo and Faccenna, 2004), and 32–30 Ma (transition from flysch to molasse sedimentation, Sinclair, 1997). Also, it remains unclear whether slab break-off in the central part of the Alps migrated laterally, and if so, in which direction; to the east, the west, or in both directions. Slab break-off in the Eastern Alps and the Carpathians must have begun well before the insertion of the Dinaridic slab into the Eastern Alps (Ustaszewski et al., 2008), i.e., before 20 Ma ago and hence could represent the lateral continuation of break-off in the Central Alps. Judging from the geometry depicted in Fig. 3a, slab tearing beneath the Western Alps only occurred very recently, i.e., after shortening across the Western Alps stopped and gave way to extension (Sue and Tricart, 2003).

4.4.2. Rollback subduction of the remaining Ligurian Ocean and backarc extension in the Western Mediterranean

Subduction of the narrow western branch of the Ligurian Ocean is inferred to have ended when continental lithosphere of the Iberian–European margin entered the subduction zone sometime around 35 Ma (Fig. 14a), triggering W- and NW-directed subduction and E-directed rollback of the broad, remaining expanse of Eastern Ligurian Ocean from about 30 Ma onwards (Fig. 14b, age constraints in Rosenbaum et al., 2002b; Faccenna et al., 2004; Molli, 2008). This subduction initiated to the east of Corsica, then retreated to the east and southeast (e.g., Cavazza et al., 2004 and references therein), stranding previously subducted and exhumed oceanic and continental units in its hangingwall, e.g., on the eastern “Alpine” part of Corsica (Fig. 14b). The jump in the location and polarity of Ligurian subduction from SE- to NW-dipping may explain why the Western Alps and Corsica never reached a truly collisional stage, with no evidence of Barrovian metamorphism related to crustal thickening, and with HP rocks having experienced only greenschist-facies overprint (Oberhänsli et al., 2004).

The minor convergence of Africa and Adria between 35 and 20 Ma in our reconstruction necessitates subduction of a small part of the Ionian Sea during this time (Fig. 14b). We emphasize that the proposed evolution for the area of the Ionian Sea is as speculative as the age of the Ionian lithosphere is poorly constrained (see Section 4.2.4) Whatever the age and nature of the lithosphere beneath the Ionian Sea (oceanic or thinned continental?), the lithosphere remaining after this Oligo-Miocene subduction appears to have been sufficiently old and dense to facilitate expansion of the retreating Calabrian arc–trench system into the remaining oceanic embayment area, as originally proposed by Malinverno and Ryan (1986). Today, the Straight of Sicily is characterized by active NW–SE extension that overprints SE-directed thrusts related to Calabrian subduction (Corti et al., 2006), in accordance with ongoing counterclockwise rotation of the Adriatic microplate with respect to Africa and Europe (e.g., Calais et al., 2001; Battaglia et al., 2004; Vrabec et al., 2006; Weber et al., 2006).

From Late Oligocene time to the present, backarc extension accommodated rollback subduction of the eastern Ligurian Ocean and led to the opening first of the Liguro-Provencal Basin (Oligo-Miocene, e.g., Séranne, 1999) and later of the Tyrrhenian Basin (Pliocene–Recent, e.g., Doglioni et al., 1997; Séranne, 1999; Faccenna et al., 2004). This left extensional allochthons of the Iberian margin (Corsica and Sardinia) and the Alkapeca continental fragment (in Calabria) stranded in the highly distended hangingwall of the retreating trench (Fig. 1).

A different evolution took place southwest of the North Balearic Transform, where extensional allochthons of Iberia (Balearic Islands) were stranded in the Alboran Sea as the Gibraltar arc expanded first southward, then westward to Gibraltar following collision with Africa (e.g., Royden, 1993; Rosenbaum et al., 2002b; Spakman and Wortel, 2004). Because of the peculiar evolution of the Betic-Rif arc involving large Miocene clockwise block rotations (Rosenbaum et al., 2002b), the subduction polarity remained unchanged during the Miocene in the Betic Cordillera, in contrast to the polarity switch that occurred in the Corsica–Apennine system. This led to a two-stage subduction history in the Betics associated with SE-directed subduction: pre-Oligocene subduction (Lonergan, 1993; Platt et al., 2005) followed by Miocene shortening and subduction along the southern margin of Iberia that was contemporaneous with rollback subduction (Platt et al., 2006; Platt, 2007). This second stage of subduction was contemporaneous with extension of the Alboran upper plate and removal of large parts of the former upper mantle below the Betics and their former northeastern continuation to Corsica.

5. How much of Alpine Tethys can we see at depth?

To answer this question, we compared the area of subducted lithosphere in our plate-motion reconstructions with the area of subducted lithosphere estimated from positive P-wave anomalies beneath the Alpine and Western Mediterranean regions (Fig. 17). Ideally, these areas should be identical, but the fact that they are not (Fig. 18) tells us something about tomographic imaging, the preservation potential of slabs and/or about the validity of our reconstructions and underlying assumptions.

To estimate the amount of subducted lithosphere in the mantle transitional zone, we measured a horizontal slice through the thickest and broadest part of the large positive P-wave anomaly within the mantle transition zone underlying the western Mediterranean Sea and its surrounding Cenozoic mountain belts at 550 km depth (Fig. 17a, courtesy of W. Spakman). In relating this anomaly to Alpine Tethys (e.g., Spakman and Wortel, 2004; Piromallo and Faccenna, 2004; Hafkenscheid et al., 2006), we follow previous interpretations that such anomalies represent cooler and denser lithosphere that was entrained during subduction. Although such anomalies may have moved somewhat with respect to the global hot-spot reference frame (van der Meer et al., 2009), we note that the NW boundary of the large anomaly forms a line from beneath the Western Alps to the Betic Cordillera and corresponds almost exactly with the NW limit of Cenozoic, SE-directed Alpine subduction in our reconstructions (compare Fig. 14a with Fig. 17a). Only beneath the Alps does this positive anomaly extend somewhat beyond the Alpine front (Lombardi et al., 2009), suggesting that there has been little, if any, motion of the present-day European plate with respect to the slabs in the mantle transitional zone.

For counting purposes, we delimited the anomaly at 550 km depth in Fig. 17a with the smallest positive contour (+0.09%) and, for comparison, with an intermediate positive contour (+0.44%) that can be traced almost continuously from the Gibraltar Arc to the eastern Carpathians (red contours outlined in Fig. 17a). In the east, the contours were drawn so as to avoid inclusion of the large Aegean anomaly that lies outside the area considered in our reconstructions. We measured slab area rather than volume because the real thickness of the slab material making up the P-wave anomaly in this slab graveyard is almost impossible to determine due to blurring of the slab images near the 670 km discontinuity. The blurring of the slab images decreases upwards where defocusing is less severe, such that inclined slabs in Miocene-to-recent subduction zones are imaged more clearly (e.g. Calabrian slab in Fig. 3e). The total area of the hanging slabs plus the area of subhorizontal lithosphere beneath the

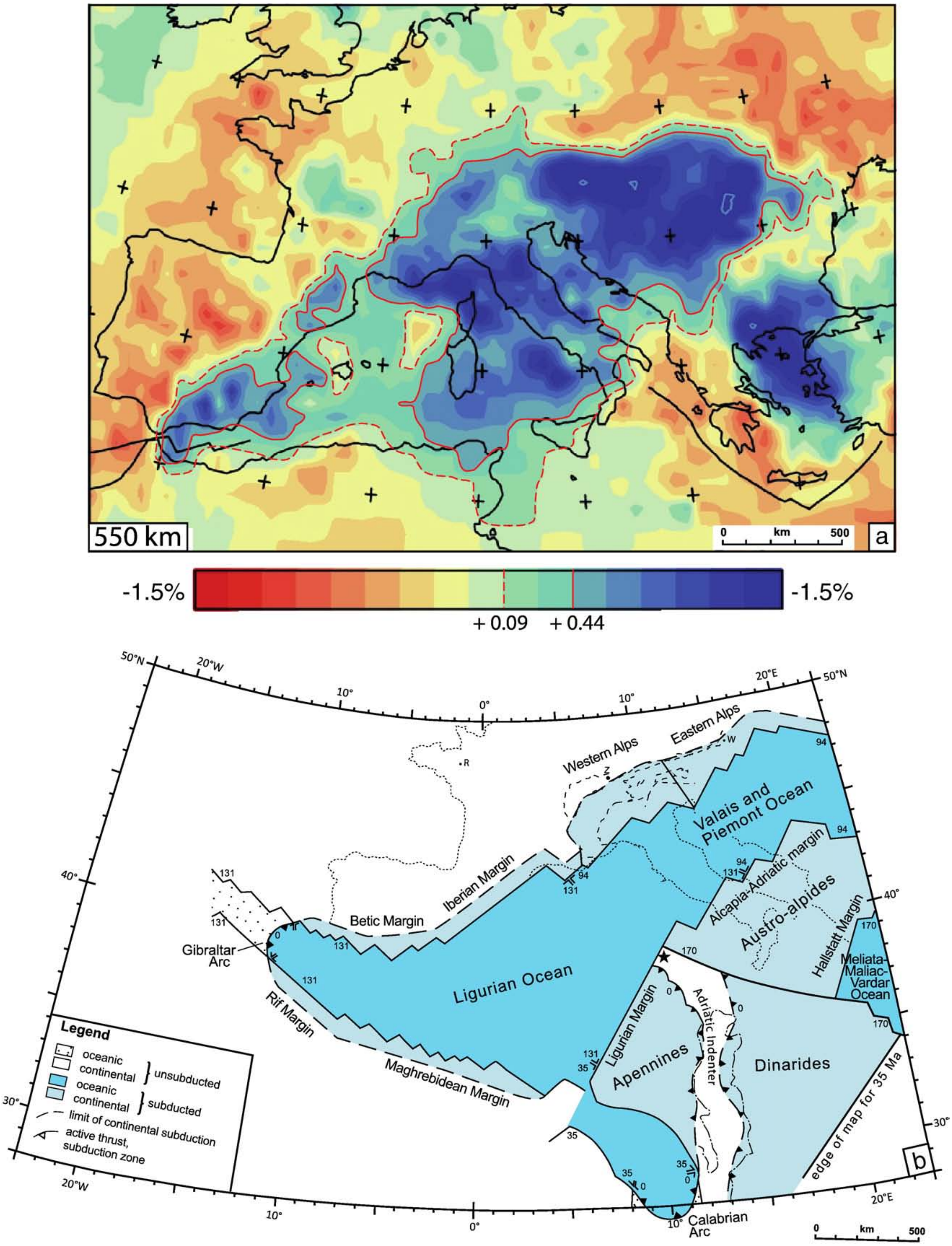


Fig. 17. Subducted lithosphere in the Alps and Mediterranean region. (a) P-wave anomalies at 550 km depth interpreted to be slabs of lithospheric mantle subducted in Late Cretaceous and Cenozoic time (courtesy of W. Spakman). Dashed and solid red lines mark the +0.09% and +0.44% contour lines, respectively, that enclose the positive P-wave anomaly and are used to estimate the amount of lithosphere in the mantle transitional zone in Fig. 18; (b) total area of subducted material comprising oceanic (dark blue) and continental margin (light blue) lithosphere. See text for details of construction. Areal estimates from a and b are shown in the right and left columns of Fig. 18, respectively.

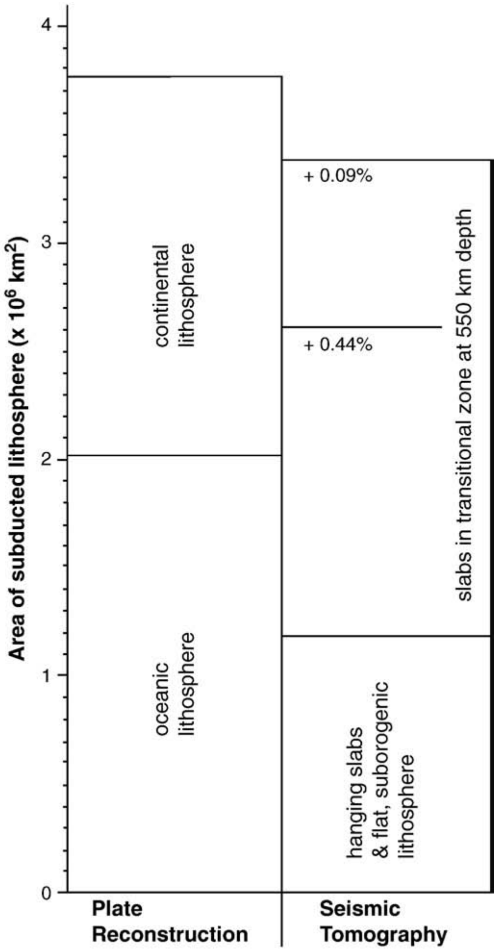


Fig. 18. Comparison of area of subducted lithosphere estimated from seismic tomograms (Fig. 17a, Table 2) and from the plate reconstruction in this paper (Fig. 17b).

present mountain belts up to their thrust fronts were estimated by multiplying the lateral extent of the slab segments in horizontal tomographic slices by their lengths measured in vertical tomographic sections. The average areas for these segments are listed together with the published tomographic sections in Table 2.

The amount of lithosphere subducted in our plate reconstructions was estimated from the composite map of Alpine Tethys shown in Fig. 17b. This map was created by successively superposing plate reconstruction maps for the maximum extent of the Valais–Piemont Ocean (94 Ma, Fig. 10b), the eastern and western branches of the Ligurian Ocean (131 Ma, Fig. 8b), the Meliata–Maliac–Vardar Ocean (170 Ma, Fig. 8a) and the Ionian Sea (35 Ma, Fig. 14a), then adding the extent of Cretaceous and Cenozoic orogenic lithosphere up to the present orogenic fronts and subduction zones. Where constraints on shortening are lacking, we assumed the width of the subducted part of the continental margins to have been about 100 km, while noting that the actual width of the margins may have been greater (Lavier and Manatschal, 2006). The various segments of passive margins and thrust fronts in Fig. 17b are labelled with ages (small numbers) that indicate the map from which they originate. We note that due to the complex motion of microplates throughout the evolution of Alpine Tethys, this composite map cannot simply be placed on top of the present-day tomogram of the Western Mediterranean in order to determine the former location of subducted lithosphere. An intriguing feature shown by this map and quantified in Fig. 18 is that almost half of the total subducted lithospheric mantle is continental.

Fig. 18 shows that the area of subducted lithosphere imaged as a positive anomaly within the +0.09% contour in the mantle transition zone beneath the Western Mediterranean Sea and its surrounding Cenozoic mountain belts amounts to about 90% of the lithosphere predicted in our plate reconstruction to have been subducted since Late Mesozoic time. The flat-lying parts of slabs residing in the “slab graveyard”, i.e., in the mantle transition zone, make up about 65% of the imaged slab material, with the remaining 35% found in the inclined slabs hanging beneath the orogens and in the adjoining, flat-lying parts of the lithosphere that extend from top ends of the inclined slabs to the orogenic fronts, as depicted in Fig. 17b.

The 10% discrepancy between imaged (+0.09% contour) and reconstructed areas of subduction is surprisingly small considering the uncertainties in our plate-kinematic reconstruction, which pertain chiefly to the widths of the subducted rifted margins as well as to the estimates of shortening in the Alpine nappes. Because the shortening estimates are minimum rather than maximum values (see Section 2.3), the actual difference in reconstructed and observed amounts of subduction is probably greater than shown in Fig. 18. Moreover, the agreement between subducted and reconstructed lithospheric areas depends on the velocity contour chosen. The misfit obviously increases if higher positive contour values are used to delimit the subducted slabs in the transitional zone. Yet, even using the more conservative +0.44% contour interval yields an imaged subducted area that is still 70% of the reconstructed area of subduction (Fig. 18). Given the current resolution of seismic tomography and the expected velocity anomalies for subducted slab material, the 70% value is more realistic than the 90% estimate based on the +0.09% contour.

If we assume our reconstruction to be correct and the 10–30% discrepancy between imaged and reconstructed areas of subducted lithosphere to be significant, then there are several possible explanations for the “missing” slab material: (1) Two slabs that descended at different times may lie on top of each other in some parts of the mantle transitional zone. Because we assumed that the positive P-wave anomaly in Fig. 17a is everywhere no thicker than a single slab (100 km), areas that actually contain overlapping parts of slabs were not counted as such, leading to a shortfall in the estimated area of subducted material. Indeed this is probably the case beneath the present area of the Ligurian Sea, Corsica, and the Alps–Apennines junction, where the Miocene slab associated with NW-dipping Apenninic rollback subduction is superposed on top of the Cenozoic slab associated with SE-dipping Alpine subduction. Similarly superposed slabs may well exist beneath the Dinarides. Unfortunately, severe defocusing at depths greater than 400 km robs us of the resolution necessary to image these stacked slabs in the mantle transition zone; (2) Some slab material may have become seismically transparent, either due to thermal expansion within the transition zone or to an endothermic phase change when descending into the more viscous lower mantle (Hager, 1984). Possible

Table 2
Area of subducted slabs and flat-lying lithosphere behind the orogenic fronts.
Sources: (1) Lippitsch et al. (2003); (2) Schmid et al. (2004b); (3) Bijwaard and Spakman (2000); (4) Piromallo and Morelli (2003); (5) Ustaszewski et al. (2008); (6) new tomograms courtesy of W. Spakman; (7) Wortel and Spakman (2000); (8) Spakman and Wortel (2004).

Region	Area of subducted slabs and flat-lying sub-orogenic lithosphere
Western Alps[1, 2]	130,075 km^2
Eastern Alps, Dinarides[1, 3, 4, 5, 6]	243,325 km^2
Western Carpathians[7] (not including Vrancea slab)	All at depth in the transitional zone
Northern Apennines[8]	173,250 km^2
Southern Apennines[8]	77,000 km^2
Calabrian Arc[8]	142,500 km^2
Sicily[8]	90,000 km^2
Eastern Algeria[8]	133,500 km^2
Gibraltar Arc and Betic Cordillera[8]	190,000 km^2
Total area (hanging slabs and subhorizontal lithosphere behind the orogenic fronts)	1,179,650 km^2

down-welling of slab material into the lower mantle can be inferred from local protuberances of seismically faster material imaged below the base of anomaly A in Fig. 3b and c. This is not surprising considering that some of this subducted lithosphere was already older than 100 Ma when subduction began and had reached the transition zone by Late Cretaceous time. Faccenna et al. (2003) speculate that slabs residing in the transition zone for longer than about 50 Ma become gravitationally unstable and sink slowly into the more viscous lower mantle. Thus, the high-velocity mantle anomalies in tomograms still may provide only a minimum estimate of the volume of Tethyan lithosphere actually subducted. The visibility of slabs in the mantle appears to depend on several factors that are still poorly constrained, including the age of the lithosphere at the time of subduction, the time spent by the subducted lithosphere in the mantle and on lateral variations in the thermo-mechanical properties of the transition zone.

6. What governed the subduction of Alpine Tethys?

The forces that drive ancient subduction systems—including those leading to the closure of Alpine Tethys—can only be inferred by comparing the kinematics of past plate motion with present plate dynamics. Yet in the case of Alpine Tethys, we have shown that the plate motions leading to the modern Western Mediterranean configuration (Fig. 1) changed repeatedly since 170 Ma, when Alpine Tethys began to open as a branch of the Atlantic Ocean (Fig. 8a). Quantifying the path of the Adriatic microplate in our reconstructions (Fig. 7) has allowed us to discern the following three stages of plate motion that were characterized by different styles of subduction and orogenesis:

Stage I: From 170 to 84 Ma, E–W transform faulting and highly oblique shortening in the Tethyan domain initially involved subduction within the northern branch of Neotethys (Fig. 8a) followed by obduction of oceanic lithosphere onto Adria and Alcapia (Fig. 8b). This was followed by Eo-alpine orogenesis and coeval intra-oceanic subduction of part of the Ligurian Ocean (Fig. 10). This early stage of subduction was therefore induced either by ridge-push from North Atlantic spreading (including the Valais part of Alpine Tethys) or by pull from the Neotethyan slab that formed the NE edge of Alcapia and the united Adriatic–African plate (Fig. 8a,b; part of the slab labelled Meliata in Figs. 9b and 11), or by some combination of these two forces. Given the low Late Cretaceous spreading rate of the North Atlantic Ocean (ca. 1 cm yr^{-1}, Dercourt et al., 1986; Dewey et al., 1989; Rosenbaum et al., 2002a,b) and the old (70–80 My) age of the Neotethyan oceanic lithosphere at the onset of Cretaceous subduction (Fig. 6 and references therein), we favour slab pull from the east as the dominant force triggering this subduction, and ultimately the later subduction of Alpine Tethys. A further possibility is the recently proposed, unorthodox view that Cretaceous subduction in the Alps was purely intracontinental and triggered by gravitational instability resulting from prolonged cooling of Permian rift-related intrusive rocks (Schuster and Stüwe, 2008; Stüwe and Schuster, 2010). We regard this scenario as rather unlikely because Permian transtension and magmatism, which were widespread in the Alps (e.g., Ivrea Zone, Handy et al. 1999), as indeed in most of Europe (Ziegler, 1990), were not sites of Alpine subduction anywhere else. In any case, push of Africa cannot have served as a driving force during this stage, because northward motion of Africa with respect to Europe did not start before 84 Ma (Fig. 7).

We propose that Eo-alpine intracontinental subduction stripped almost the entire subcontinental mantle lithosphere from the down-going Alcapia microplate (Fig. 11). Based on this scenario, we infer that this subducted continental lithosphere presently makes up about half of the P-wave anomaly in the mantle transitional zone beneath the northern Adriatic Sea (Fig. 3b,c). Wholesale subduction of continental lithosphere has also been proposed for late Cenozoic subduction beneath the Northern Apennines (e.g., Serri et al., 1993) and Alboran–Gibraltar region (Faccenna et al., 2004) where thin crustal slivers were scraped off the down-going subcontinental mantle that was attached to negatively buoyant Ligurian oceanic lithosphere.

Stage II: From 84 to 35 Ma, NW motion of the independent Adriatic microplate resulted in subduction of the Piemont, Briançonnais and Valais parts of Alpine Tethys, as well as the remaining part of the narrow Western Ligurian Ocean beneath the evolving Western Alpine accretionary wedge (Figs. 10b, 12, and 14a). During this time, Europe did not move appreciably with respect to an absolute plate-motion reference frame (e.g., Torsvik et al., 2008, their Fig. 17). Initial subduction was slow (0.9 cm yr^{-1}, Fig. 16) as determined by the convergence rate of Africa with respect to Europe (e.g., Savostin et al., 1986; Dewey et al., 1989; Rosenbaum et al., 2002a) from 84 to 67 Ma. After 67 Ma, the rate of this SE-directed subduction of predominantly oceanic lithosphere increased to 1.5 cm yr^{-1} (Fig. 16) as derived from Adria's independent motion path in Fig. 7. The rate of Adria's northward motion thus exceeded the Africa's with respect to Europe by about 0.2 cm yr^{-1} during this time. We propose that the faster northward motion of Adria with respect to Africa between 67 and 35 Ma was accommodated by slow spreading in the Ionian Sea (Figs. 12b, 14a, and 16), possibly augmented by sporadic rifting in the Sirte Basin in Late Cretaceous and Early Cenozoic time (Fig. 12b). This pre-empted any significant Cenozoic extension and arc-type magmatism in the upper, Adriatic microplate (see Section 4.3.2), allowing Adria to retain its original thickness and rigidity and thus rendering it an effective orogenic indenter during subsequent Alpine collision.

Because Adria's NW translation away from Africa between 67 and 35 Ma cannot be explained by a push from the more slowly advancing African plate, other driving forces must have been responsible for this motion. We believe that the independent motion of Adria was driven partly by pull of the Adriatic slab descending to the NE beneath the Dinaric orogen and partly by suction in the wake of the retreating European slab that was descending to the S to SE beneath the Adriatic microplate. Already by 84 Ma, this slab had acquired a length of several hundred kilometres beneath the Adriatic part of the African plate (Fig. 13a). The pull of the European slab initiated NW-ward hinge retreat, which continued until 35 Ma in an absolute plate-motion reference frame, as approximated in our figures by the position of stable Europe (Figs. 12ab and 14a). The suction created by asthenospheric mantle flowing into the space left behind the migrating slab (Conrad and Lithgow-Bertelloni, 2002) exerted a viscous shear force on the base of the overlying Adriatic microplate, thus pulling it toward Europe faster that Africa's northward advance.

The forces that drove the Pyrenean Orogeny in latest Cretaceous to Eocene time (e.g., Choukroune, 1992; Sibuet et al., 2004) are enigmatic given that oceanic lithosphere may still have been present in the Ligurian Ocean at that time (Fig. 12); there, ongoing subduction would seem likely to have pre-empted collision in the Pyrenees. We suspect that prior Late Cretaceous strike-slip motion along the future Pyrenees (Fig. 10, see Section 4.2) had conditioned the Pyrenean lithosphere sufficiently to favour the initiation of subduction that became intracontinental in Eocene time (Sibuet et al., 2004), driven by the northward push of Africa.

Stage III: The switch in subduction polarity from a SE-dipping, “Alpine” configuration (Fig. 14a) to a NW-dipping, “Apenninic” configuration (Fig. 14b) at about 35 Ma ushered in widespread rollback subduction of the remaining parts of Alpine Tethys and dramatically changed the plate configuration to the one seen today, as depicted in Fig. 1. This “Oligocene revolution” appears to have been favoured mainly by two circumstances: First, the slowing of convergence between Africa, Adria and Europe due to a dramatic increase in the forces resisting further subduction with the onset of continent–continent collision in the Alps at about 35 Ma, and second, the presence of large areas of not-yet subducted, old (100–140 Ma) and therefore negatively buoyant oceanic lithosphere in the eastern Ligurian Ocean and the Ionian Sea (Fig. 14a).

Indeed, continental collision along most of the northern margin of the Adriatic microplate after 35 Ma (Fig. 14a) slowed Adria's northward component of motion from 1.5 to only 0.3 cm yr^{-1}, while Africa's northward motion with respect to Europe still continued at about 1 cm yr^{-1} according to the motion paths in Fig. 7 (Savostin et al., 1986). In our reconstruction, this difference in the northward convergence rates of Africa and Adria was initially taken up by slow, limited subduction of the Ionian Sea lithosphere sometime between 35 and 20 Ma (0.6 cm yr^{-1}, Fig. 16) when Adria started to rotate counter-clockwise with respect to Europe (Fig. 14a,b). However, once this admittedly hypothetical subduction stopped no later than 20 Ma, Africa–Europe convergence was accommodated entirely by the ongoing indentation of the rigid continental core of the Adriatic microplate (i.e., the *Adriatic indenter*) into the Alpine orogenic edifice. Clearly, the continued counter-clockwise rotation of Adria since the onset of collision at 35 Ma must have been driven by the push of the African plate from the south because the part of the European slab that remained attached to the crust after breaking-off of its long oceanic segment was too short to exert significant suction on the overriding plate.

Rollback subduction of the sole remaining part of Alpine Tethys, the eastern Ligurian Ocean, accelerated at about 23–20 Ma when the convergence of Africa and Europe dropped to 0.2 cm yr^{-1} (e.g., Faccenna et al., 2004 and references therein). Rapid subduction at these low plate-convergence rates was evidently driven by the pull of the gravitationally unstable Adriatic and African slabs, as already proposed by numerous authors (e.g., Royden, 1993; Spakman and Wortel, 2004). The upper Iberian–European plate stretched to accommodate this slab retreat in a highly mobile fashion as evidenced by calc-alkaline magmatism and the opening of backarc basins in the Western Mediterranean Sea (Fig. 1). The Gibraltar and Calabrian arcs at either end of the Western Mediterranean (Fig. 1) overlie narrow, highly deformable strips of slab material (Wortel and Spakman, 2000; Spakman and Wortel, 2004; Piromallo et al., 2006) that are thought to have torn from the original host African and Adriatic slabs, and migrated laterally to the W and E, respectively, during the last 5–10 Ma (Royden, 1993; Faccenna et al., 2004 and references therein). Note that in the case of the Betic Cordillera (i.e., the northern half of the Gibraltar arc) it was the Iberian plate that continued to subduct to the south, i.e., with the same polarity as prior to 35 Ma. The processes of slab separation and arc formation are still unclear, but experiments conducted with both analogue and numerical models indicate that such narrow slab strips individuate from a larger slab when asthenospheric mantle trapped between the retreating slab and the underlying mantle transitional zone becomes overpressured and circulates laterally, thinning the slab to the point of vertical rupture. These ruptures or gaps segment the slab and allow the overpressured asthenosphere to escape toroidally up and around the gaps' vertical edges, curling these edges to form an arc and facilitating further rollback of the narrow slab segment (e.g., Funicello et al., 2006; Piromallo et al., 2006, Royden and Husson, 2006). This mechanism is plausible when applied to the Calabrian slab, which is flanked on either side by slab gaps beneath the Southern Apennines and Straight of Sicily (Faccenna et al., 2004; Spakman and Wortel, 2004); these gaps presumably opened during the last 10 Ma, allowing the slab to retreat more rapidly to the SE into the former Ionian Sea embayment (Faccenna et al., 2004). A similar slab gap has been imaged to the southeast of the Gibraltar arc (Spakman and Wortel, 2004, their Fig. 2.4) and corresponds at the surface with an accommodation zone of sinistral transform motion that dissects the mountain belts of northern Africa (Faccenna et al., 2004, their Figs. 3 and 4).

Finally, we address the forces that drove the switch in subduction polarity in the area south of the Ligurian Alps (location in Figs. 1 and 4) from a SE-dipping Alpine polarity until just after 35 Ma (Fig. 14a) to the W-dipping Apenninic polarity still active today (Figs. 1 and 14b). Break-off of the segment of a formerly continuous Alpine slab that was situated to the SW of present-day Liguria (Fig. 14a) is certainly a prerequisite for this switch, which we believe was triggered by collision between Iberia and the Alkapeca continental fragment after the buoyant Iberian margin entered the Alpine subduction zone (compare Fig. 12b with Fig. 14a). Continued NNW–SSE convergence was then accommodated along the new, NW- to W-dipping Apenninic subduction zone that formed along the eastern margin of the Alkapeca continental fragment, as shown in Fig. 14b and already discussed in Section 4.4.2. The along-strike change of Miocene-to-present subduction polarity in Liguria requires a vertical slab tear in that area (Vignaroli et al., 2008), which we propose nucleated along inherited lithospheric structures, specifically the E–W trending Mesozoic transform systems located at the northern tip of the Alkapeca continental fragment (Fig. 14a). These old transforms represented first-order heterogeneities, having previously accommodated differential sea-floor spreading of the Piemont and Liguria Oceans (Fig. 8) and subsequent eastward motion of the Iberian microplate with respect to Europe (Fig. 10). While Miocene eastward migration of the new, W- and eventually SW-dipping Adriatic slab beneath the Northern Apennines was driven by the negative buoyancy of the eastern Ligurian oceanic lithosphere, convergence across the then still-active Alpine subduction system in the Western Alps was driven by the slow NW-ward indentation of the continental part of the rotating Adriatic microplate, i.e., the NW corner of the Adriatic indenter (e.g., Laubscher, 1991).

7. Conclusions

Our reconstruction of Mesozoic to Cenozoic microplate motions in the Western Mediterranean area is surprisingly consistent with the record of subduction provided by P-wave anomalies in the mantle (e.g., Spakman and Wortel, 2004), especially given the considerable ambiguities of both the geology and the mantle tomography. This consistency suggests, but by no means proves, that the intermittently independent motion of microplates presented here between the major plates of Europe and Africa are valid within error.

Our reconstruction also casts both new light as well as enigmatic shadows on the long-standing debate over the fate of Alpine Tethys and its relationship to the Cretaceous–Cenozoic subduction and collisional belts of the Western Mediterranean. In recent years, this debate has centered on whether the Ligurian part of Alpine Tethys has been subducting beneath the European plate since Late Cretaceous time (so-called "single subduction models", e.g., Biju-Duval et al., 1977; Dercourt et al., 1986; Jolivet and Faccenna, 2000; Vignaroli et al., 2008), or alternatively, whether this subduction zone was originally SE-dipping beneath the African plate until the onset of Oligocene Alpine collision, when its polarity switched to NW-dipping beneath the European plate and the trend of the subduction zone was subsequently modified by rollback of the lower plate and arc formation ("two-subduction models", e.g., Elter and Pertusati, 1973; Doglioni et al., 1999; Michard et al., 2002, 2006; this paper). In all of these models, the Cenozoic subduction zone in the Piemont part of Alpine Tethys was SE-dipping, in accordance with the top-NW transport direction of Alpine nappes containing Piemont–Ligurian ophiolites and Cenozoic HP rocks, but there is still no consensus on the pre-Neogene subduction direction in the Betic Cordillera of southern Spain where interpretations are diametrically opposed (e.g., NW-directed subduction: Zeck, 1997; Platt, 2007; SE-directed subduction: Michard et al., 2002). Nevertheless, the occurrence of nappes with an Alpine-vergence (i.e., top-Europe) that was later refolded and thrust in the opposite direction (i.e., "backthrusted") in both the Northern and Southern Apennines (Elter and Pertusati, 1973; Bonardi et al., 2001; Molli, 2008) and the Betic Cordillera (Michard et al. 2002) is a strong argument in favour of the "two-subduction" model adopted in our plate reconstruction, at least for the closure of Alpine Tethys from Latest Cretaceous time (84 Ma) onward when both Africa and Adria converged with Europe. These backfolded units are what originally inspired Argand (1924) to propose the idea—based on cylindrism—that the Apennines and Maghrebides of northern Africa were the lateral continuation of the famous backfolds in the Western Alps.

The geological–geophysical evidence presented in this paper for intermittently independent motion of up to five microplates (Adria, Iberia, Alkapecia, Alcapia, Tiszia) between Europe and Africa supports a view that is perhaps even more radical than the two-subduction zone model; this is the idea that the subduction of Alpine Tethys was conditioned by transform tectonics in Late Jurassic–Early Cretaceous time and was actually triggered from the east by Eo-alpine orogenesis and the subduction of the northern branch of Neotethys. The huge tomographic anomaly in the mantle transitional zone beneath the Alps, Carpathians and northern Adriatic Sea is testimony to this earliest stage in the subduction of Alpine Tethys, which began as a single slab but eventually segmented and acquired its irregular, arcuate trace in map view when the Alpine collision began and the convergence rate between Africa, Adria and Europe dropped to below 0.5 cm yr^{-1}. Although Alpine Tethys no longer exists at the surface, its influence on the neotectonics of the Western Mediterranean area is still evident as the remaining slab segments continue to pull and the Adriatic microplate is consumed along subduction zones beneath the Apennines and Dinarides, even as subduction beneath the Calabrian and Gibraltar arcs has almost come to a halt (Fig. 1).

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References

Amato, J.M., Johnson, C.M., Baumgartner, L.P., Beard, B.L., 1999. Rapid exhumation of the Zermatt–Saas ophiolite deduced from high-precision Sm–Nd and Rb–Sr geochronology. Earth and Planetary Science Letters 171 (3), 425–438.

Ampferer, O., 1906. Über das Bewegungsbild von Faltengebirgen. Jahrbuch des Geologischen Reichsanstalt (Wien) 56, 539–622.

Argand, E., 1911. Les nappes de recouvrement des Alpes Pennines et leurs prolongements structuraux. Beiträge zur Geologischen Karte der Schweiz, Neue Folge 31, 1–25.

Argand, E., 1924. Des Alpes et de l'Afrique. Bulletin de la Société Vaudoise des Sciences Naturelles 55, 233–236.

Auer, M., Eisbacher, G.H., 2003. Deep structure and kinematics of the Northern Calcareous Alps (TRANSALP Profile). International Journal of Earth Sciences 92, 210–227.

Babist, J., Handy, M.R., Konrad-Schmolke, M., Hammerschmidt, K., 2006. Precollisional multistage exhumation of the subducted continental crust: the Sesia zone, western Alps. Tectonics 26, TC6008. doi:10.1029/2005TC001927.

Barbieri, C., Carrapa, B., Di Giulio, A., Wijbrans, J., Murrell, G.R., 2003. Provenance of Oligocene synorogenic sediments of the Ligurian Alps (NW Italy): inferences in belt age and cooling history. International Journal of Earth Sciences 92, 758–778.

Battaglia, M., Murray, M.H., Serpelloni, E., Bürgmann, R., 2004. The Adriatic region: an independent microplate within the Africa–Eurasia collision zone. Geophysical Research Letters 31, L09605. doi:10.1029/2004GL019723.

Baumgartner, P.O., Martire, L., Gorican, S., O'Dogherty, L., Erba, E., Pillevuit, A., 1995. New Middle and Upper Jurassic radiolarian assemblages co-occurring with ammonites and nannofossils from the Southern Alps (Northern Italy). In: Baumgartner, P.O., O'Dogherty, L., Gorican, S., Urquhart, E., Pillevuit, A., De Wever, P. (Eds.), Middle Jurassic to Lower Cretaceous Radiolaria of Tethys: Occurrences, Systematics, Biochronology. Mémoires de Géologie (Lausanne), pp. 737–750.

Bayer, R., Le Mouel, J.-L., Le Pichon, X., 1973. Magnetic anomaly pattern in the Western Mediterranean. Earth and Planetary Science Letters 19, 168–176.

Becker, B. 1993. The Structural Evolution of the Radstadt Thrust System, Eastern Alps, Austria—Kinematics, Thrust Geometries, Strain Analysis. PhD. thesis, Univ. Tübingen, Germany, 92 pp.

Beltrando, M., Rubatto, D., Compagnoni, R., Lister, G., 2007. Was the Valaisan basin floored by oceanic crust? Evidence of Permian magmatism in the Versoyen Unit (Valaisan domain, NW Alps). Ofioliti 21, 85–99.

Berger, A., Bousquet, R., 2008. Subduction-related metamorphism in the Alps: review of isotopic ages based on petrology and their geodynamic consequences. In: Siegesmund, S., Fügenschuh, B., Froitzheim, N. (Eds.), Tectonic Aspects of the Alpine–Dinaride–Carpathian System: Geological Society, London, Special Publications, 298, pp. 117–144.

Bertotti, G., Picotti, V., Bernoulli, D., Castellarin, A., 1993. From rifting to drifting: tectonic evolution of the South-Alpine upper crust from the Triassic to the Early Cretaceous. Sedimentary Geology 86, 53–76.

Bezert, P., Caby, R., 1988. Sur l'age post-bartonien des événements tectono-métamorphiques alpines en bordure orientale de la Corse crystalline. Bulletin de la Société Géologique de France 8, 965–971.

Bigi, G., Castellarin, A., Catalano, R., Coli, M., Cosentino, D., Dal Piaz, G.V., Lentini, F., Parotto, M., Patacca, E., Praturlon, A., Salvini, F., Sartori, R., Scandone, P. Vai, G., 1989. Synthetic structural kinematic map of Italy, Sheets 1 and 2, C.N.R., Progetto Finalizzato Geodinamica, SELCA Firenze.

Biino, G., Compagnoni, R., Naldi, M., 1988. The Canavese zone near Ivrea (Western Alps). Rendiconti. Società Geologica Italiana 11, 85–88.

Biju-Duval, B., Dercourt, J., Le Pichon, X., 1977. From the Tethys ocean to the Mediterranean seas: a plate tectonic model of the evolution of the western Alpine system. In: Biju-Duval, B., Montadert, L. (Eds.), International Symposium on the Structural History of the Mediterranean Basins. Split, Yugoslavia, Edition Technip, Paris, pp. 143–164.

Bijwaard, H., Spakman, W., 2000. Non-linear global P wave tomography by iterated linearized inversion. Geophysical Journal International 141, 71–82.

Bill, M., Bussy, F., Cosca, M., Masson, H., Hunziker, J.C., 1997. High precision U–Pb and 40Ar/39Ar dating of an Alpine ophiolite (Gêts nappe, French Alps). Eclogae Geologicae Helvetiae 90, 43–54.

Bill, M., O'Dogherty, L., Guex, J., Baumgartner, P.O., Masson, H., 2001. Radiolarite ages in Alpine–Mediterranean ophiolites: constraints on the oceanic spreading and the Tethys–Atlantic connection. Geological Society of America Bulletin 113 (1), 129–143.

Bonardi, G., Cavazza, W., Perrone, V., Rossi, S., 2001. Calabria-Peloritani terrane and northern Ionian Sea. In: Vai, G.B., Martini, I.P. (Eds.), Anatomy of an Orogen: The Apennines and Adjacent Mediterranean Basins. Kluwer Academic Press, pp. 287–306.

Boullin, J.P., Durand-Delga, M., Olivier, P., 1986. Betic-Rifain and Tyrrhenian Arcs: distinctive features, genesis and development stages. In: Wezel, F.C. (Ed.), The Origins of Arcs. Elsevier, pp. 281–304.

Bousquet, R., Oberhänsli, R., Goffé, B., Jolivet, L., Vidal, O., 1998. High-pressure–low-temperature metamorphism and deformation in the Bündnerschiefer of the Engadine window: implications for the regional evolution of the eastern Alps. Journal of Metamorphic Geology 16, 657–674.

Bousquet, R., Goffé, B., Vidal, O., Oberhänsli, R., Patriat, M., 2002. The tectono-metamorphic history of the Valaisan domain from the Western to the Central Alps: new constraints on the evolution of the Alps. Geological Society of America Bulletin 114 (2), 207–225.

Bousquet, R., Goffé, B., Wiederkehr, M., Koller, F., Schmid, S.M., Schuster, R., Engi, M., Martinotti, G., 2008. Metamorphism of metasediments at the scale of an orogen: a key to the Tertiary geodynamic evolution of the Alps. In: Siegesmund, S., Fügenschuh, B., Froitzheim, N. (Eds.), Tectonic Aspects of the Alpine–Dinaride–Carpathian: Geological Society, London, Special Publication, 298, pp. 393–411.

Brunet, C., Monié, P., Jolivet, L., Cadet, J.-P., 2000. Migration of compression and extension in the Tyrrhenian Sea, insights from 40Ar/39Ar ages on micas along a transect from Corsica to Tuscany. Tectonophysics 321, 127–155.

Bucher, S., Bousquet, R., 2007. Metamorphic evolution of the Briançonnais Units along the ECORS-CROP profile (Western Alps): new data on metasedimentary rocks. Swiss Journal of Geosciences 100, 227–242.

Bucher, S., Schmid, S.M., Bousquet, R., Fügenschuh, B., 2003. Late-stage deformation in a collisional orogen (Western Alps): nappe refolding, back-thrusting or normal faulting? Terra Nova 15 (2), 109–117.

Bucher, S., Ulardic, C., Bousquet, R., Ceriani, S., Fügenschuh, B., Schmid, S.M., 2004. Tectonic evolution of the Briançonnais units along the ECORS-CROP transect through the Italian–French Western Alps. Eclogae Geologicae Helvetiae 97, 321–345.

Burbank, D.W., 2002. Rates of erosion and their implications for exhumation. Mineralogical Magazine 66 (1), 25–52.

Burg, J.P., van den Driessche, J., Brun, J.P., 1994. Syn- to post-thickening extension in the Variscan Belt of Western Europe: modes and structural consequences. Géologie de la France 3, 33–51.

Calais, E., Nocquet, J.-M., Jouanne, F., Tardy, M., 2001. Current strain regime in the Western Alps from continuous Global Positioning System measurements, 1996–2001. Geology 30, 651–654.

Capitanio, F.A., Goes, S., 2006. Mesozoic spreading kinematics: consequences for Cenozoic Central and Western Mediterranean subduction. Geophysical Journal International 165 (3), 804–816. doi:10.1111/j.1365-246X.2006.02892.x.

Capitanio, E.A., Faccenna, C., Funiciello, R., 2009. The opening of the Sirte basin: result of slab avalanching? Earth and Planetary Science Letters 285, 210–216.

Carmignani, L., Conti, P., Cornamusini, G., Meccheri, M., 2004. The internal Northern Apennines, the northern Tyrrhenian Sea and the Sardinia-Corsica block. In: Crescenti, U., D'Offizi, S., Merlino, S., Sacchi, L. (Eds.), Geology of Italy. Special Volume, Italian Geological Society, IGC 32, Florence 2004, Società Geologica Italiana, Roma, pp. 59–77.

Caron, J.M., 1994. Metamorphism and deformation in Alpine Corsica. Schweizerische Mineralogische und Petrographische Mitteilungen 7, 105–114.

Caron, M., Dössegger, R., Steiger, R., Trümpy, R., 1982. Das Alter der jüngsten Sedimente der Ortler-Decke (Oberostalpin) in der Val Trupchun (Schweizerischer Nationalpark, Graubünden). Eclogae Geologicae Helvetiae 75, 159–169.

Caron, C., Homewood, P., Wildi, W., 1989. The original Swiss Flysch: a reappraisal of the type deposits in the Swiss Prealps. Earth Science Reviews 26, 1–45.

Catalano, R., Dogloni, C., Merlini, S., 2001. On the Mesozoic Ionian basin. Geophysical Journal International 144, 49–64.

Catalano, R., Doglioni, C., Merlini, S., Sulli, A., 2002. The Ionian crust and the Calabrian accretionary wedge. Proceedings of Conference on Deformation, Fluid Flow and Reservoir Appraisal in Foreland Fold and Thrust Belts (American Association of Petroleum Geologists, Hedberg Conference), May 14–18, pp. 1–4.

Cavazza, W., Roure, F., Ziegler, P.A., 2004. The Mediterranean area and the surrounding regions: active processes, remnants of former Tethyan Oceans and related thrust belts. Chapter 1. In: Cavazza, W., Roure, F.M., Stampfli, G.M., Ziegler, P.A. (Eds.), The Transmed Atlas—The Mediterranean region from crust to mantle. Springer, Berlin, pp. 1–29.

Ceriani, S., Schmid, S.M., 2004. From N–S collision to WNW-directed post-collisional thrusting and folding: structural study of the Frontal Penninic Units in Savoie (Western Alps, France). Eclogae Geologicae Helvetiae 97, 347–369.

Ceriani, S., Fügenschuh, B., Schmid, S.M., 2001. Multi-stage thrusting at the "Penninic Front" in the Western Alps between Mont Blanc and Pelvoux massifs. International Journal of Earth Sciences 90, 685–702.

Chamot-Rooke, N., Rangin, C., LePichon, X., Dotmed working group 2005. DOTMED: a synthesis of deep marine data in eastern Mediterranean. Mémoires Société Géologique de France 177: 64 pp, 9 plates and CD.

Channell, J.E.T., Horvath, F., 1976. The African (Adriatic) promontory as a paleogeographical premise for Alpine orogeny and plate movements in the Carpatho-Balkan region. Tectonophysics 35, 71–101.

Channell, J.E.T., Kozur, H.W., 1997. How many oceans? Meliata, Vardar, and Pindos oceans in Mesozoic Alpine paleogeography. Geology 25 (2), 183–186.

Channell, J.E.T., d'Argenio, B., Horvath, F., 1979. Adria, the African promontory. Mesozoic Mediterranean Paleogeography: Earth Science Reviews, 15, pp. 213–292.

Channell, J.E.T., Brandner, R., Spieler, A., Smathers, N.P., 1990. Mesozoic paleogeography of the Northern Calcareous Alps—evidence from paleomagnetism and facies analysis. Geology 18, 828–831.

Chopin, C., Henry, C., Michard, A., 1991. Geology and petrology of the coesite-bearing terrain, Dora Maira massif, Western Alps. European Journal of Mineralogy 3, 263–291.

Choukroune, P., 1992. Tectonic evolution of the Pyrenees. Annual Review of Earth and Planetary Sciences 20, 143–158.

Choukroune, P., Ballèvre, M., Cobbold, P., Gautier, Y., Merle, O., Vuichard, J.-P., 1986. Deformation and Motion in the Western Alpine Arc. Tectonics 5 (2), 215–226.

Collombet, M., Thomas, J.C., Chauvin, A., Tricart, P., Bouillin, J.P., Gratier, J.P., 2002. Counter-clockwise rotation of the western Alps since the Oligocene: new insights from paleomagnetic data. Tectonics 21/4. doi:10.1029/2001TC901016.

Compagnoni, R., Hirajima, T., Chopin, C., 1995. Ultra-high pressure metamorphic rocks in the western Alps. In: Coleman, R.G., Wang, X. (Eds.), Ultrahigh-pressure Metamorphism. Cambridge University Press, New York, pp. 206–243.

Conrad, C.P., Lithgow-Bertelloni, C., 2002. How mantle slabs drive plate tectonics. Science 298. doi:10.1126/science.1074161.

Corti, G., Cuffaro, M., Doglioni, C., Innocenti, F., Manetti, P., 2006. Coexisting geodynamic processes in the Sicily Channel. Geological Society of America Special Paper 409, 83–96.

Costa, S., Caby, R., 2001. Evolution of the Ligurian Tethys in the Western Alps: Sm/Nd and U/Pb geochronology and rare-earth element geochemistry of the Montgenèvre ophiolite (France). Chemical Geology 175, 449–466.

Crisci, C.M., Ferrara, G., Mazzuoli, R., Rossi, P.M., 1984. Geochemical and geochronological data on Triassic volcanism of the Southern Alps of Lombardy (Italy): genetic implications. Geologische Rundschau 73 (1), 279–292.

Dal Piaz, G.V., 1999. The Austroalpine-Piedmont nappe stack and the puzzle of western Alpine Tethys. Memorie di Scienze Geologiche 51, 155–176.

Dal Piaz, G.V., Zirpoli, G., 1979. Occurrence of eclogite relics in the ophiolite nappe from Marine d'Albo, N-Corsica. Neues Jahrbuch Mineralogische Mitteilungen 3, 118–122.

Dal Piaz, G.V., Hunziker, J.C., Martinotti, G., 1972. La Zone Sesia-Lanzo e l'evoluzione tettonico-metamorfica delle Alpi Nordoccidentali interne. Memorie della Società Geoligica Italiana 11, 433–460.

Decandia, F.A., Elter, P., 1972. La 'zona' ofiolitifera del Bracco' nel settore compreso tra Levanto e la Val Graveglia (Appennino ligure). Memorie della Società Geoligica Italiana 11, 503–530.

Dercourt, J., 2002. Géologie et géodynamique de la France Outre-mer et européenne. Dunot, Paris. (336 pp.).

Dercourt, J., Zonenshain, L.P., Ricou, L.-E., Kazmin, V.G., Le Pichon, X., Knipper, A.L., Grandjaquet, C., Sbortshikov, I.M., Geyssant, J., Lepvrier, C., Pechersky, D.H., Boulin, J., Sibuet, J.-C., Savostin, L.A., Sorokhtin, O., Westphal, M., Bazhenov, M.L., Lauer, J.P., Bijou-Duval, B., 1986. Geological evolution of the Tethys belt from the Atlantic to the Pamirs since the Lias. Tectonophysics 123, 241–315.

Desmons, J., Compagnoni, R., Cortisogno, L., with the collaboration of Frey, M., Gaggero, L., Dallagiovanna, G., Seno, S, Radelli, L, 1999. Alpine Metamorphism of the Western Alps: I. High P/T and related pre-greenschist facies metamorphism. In: Frey, M., Desmons, J., Neubauer, F. (Eds.), The new metamorphic map of the Alps: Schweizerische Mineralogische und Petrographische Mitteilungen, 79 (1), pp. 89–110.

Desmurs, L., Manatschal, G., Bernoulli, D., 2001. The Steinmann Trinity revisited: mantle exhumation and magmatism along an ocean–continent transition: the Platte nappe, eastern Switzerland. In: Wilson, R.C.L., Whitmarsh, R.B., Taylor, B., Froitzheim, N. (Eds.), Non-volcanic Rifting of Continental Margins: A Comparison of Evidence from Land and Sea: Geological Society, London, Special Publications, 187, pp. 235–266.

Dewey, J.F., Pitman III, W.C., Ryan, W.B.F., Bonnin, J., 1973. Plate tectonics and the evolution of the Alpine system. Bulletin of the Geological Society of America 84 (10), 3137–3180.

Dewey, J.F., Helman, M.L., Turco, E., Hutton, D.H.W., Knott, S.D., 1989. Kinematics of the Western Mediterranean. In: Coward, M.P., Dietrich, D., Park, R.G. (Eds.), Alpine Tectonics: Geological Society Special Publication, 45, pp. 265–283.

Di Giulio, A., Carrapa, B., Fantoni, R., Gorla, L., Valdisturlo, A., 2001. Middle Eocene to Early Miocene sedimentary evolution of the western Lombardian segment of the South Alpine foredeep (Italy). International Journal of Earth Sciences 90, 534–548.

Dieni, I., Massari, F., 1982. Présence de glaucophane détritique dans le Maastrichtien inférieur de Sardaigne orientale. Imlications géodynamiques: C. R. Acad. Sc. Paris, 295, pp. 679–682 (II).

Doglioni, C., Flores, G., 1997. Italy. In: Moores, E.M., Fairbridge, R.W. (Eds.), Encyclopedia of European and Asian regional geology. Chapman and Hall, London, pp. 414–435.

Doglioni, C., Gueguen, E., Sàbat, F., Fernandez, M., 1997. The Western Mediterranean extensional basins and the Alpine orogen. Terra Nova 9, 109–112.

Doglioni, C., Guegen, E., Harabaglia, P., Mongelli, F., 1999. On the origin of west-directed subduction zones and applications to the western Mediterranean. In: Durad, B., Jolivet, L., Horvath, F., Séranne, M. (Eds.), The Mediterranean Basins: Tertiary Extension within the Alpine Orogen: Geological Society of London, Special Publications, 156, pp. 541–561.

Duchêne, S., Blichert-Toft, J., Luais, B., Télouk, P., Lardeaux, J.-M., Albarède, F., 1997. The Lu–Hf dating of garnets and the ages of the Alpine high-pressure metamorphism. Nature 387, 586–588.

Egal, E., 1992. Structures and tectonic evolution of the external zone of Alpine Corsica. Journal of Structural Geology 14, 1215–1228.

Eisbacher, G.H., Brandner, R., 1996. Superposed fold-thrust structures and high-angle faults, Northwestern Calcareous Alps, Austria. Eclogea Geologica Helvetiae 89 (1), 553–571.

Eisbacher, G.H., Linzer, H.-G., Meier, L., Polinski, R., 1990. A depth-extrapolated structural transect across the Northern Calcareous Alps of western Tyrol. Eclogae Geologicae Helvetiae 83 (3), 711–725.

Elter, P., Pertusati, P.C., 1973. Considerazioni sul limite Alpi-Appennino e sulle sue relazioni con l'arco delle Alpi Occidentali. Memorie della Società Geoligica Italiana 12, 359–375.

Elter, P., Grasso, M., Parotto, M., Vezzani, L., 2003. Structural setting of the Apennine-Maghrebian thrust belt. Episodes 26 (3), 205–211.

Ernst, G., 1973. Interpretative synthesis of metamorphism in the Alps. Geological Society of America Bulletin 84, 2053–2078.

Escher, A., Beaumont, C., 1997. Formation, burial and exhumation of basement nappes at crustal scale: a geometric model based on the Western Swiss–Italian Alps. Journal of Structural Geology 19 (7), 955–974.

Faccenna, C., Jolivet, L., Piromallo, C., Morelli, A., 2003. Subduction and the depth of convection in the Mediterranean mantle. Journal of Geophysical Research 10 (B2). doi:10.1029/2001JB001690.

Faccenna, C., Piromallo, C., Crespo-Blanc, A., Jolivet, L., Rossetti, F., 2004. Lateral slab deformation and the origin of the western Mediterranean arcs. Tectonics 23 (TC1012). doi:10.1029/2002TC001488.

Faryad, S.W., Henjes-Kunst, F., 1997. Petrological and K–Ar and ^{40}Ar–^{39}Ar age constraints for the tectonothermal evolution of the high-pressure Meliata unit, Western Carpathians (Slovakia). Tectonophysics 280, 141–156.

Faupl, P., Wagreich, M., 2000. Late Jurassic to Eocene Paleogeography and geodynamic evolution of the Eastern Alps. Mitteilungen der Österreichischen Geologischen Gesellschaft 92, 79–94.

Federico, L., Crispini, L., Scambelluri, M., Capponi, G., 2007. Ophiolite mélange zone records exhumation in a fossil subduction channel. Geology 35 (6), 499–502.

Ferrando, S., Bernoulli, D., Compagnoni, R., 2004. The Canavese zone (internal Western Alps): a distal margin of Adria. Schweizerische Mineralogische und Petrographische Mitteilungen 84, 237–256.

Ferrière, J., 1982. Paléogéographies et tectoniques superposés dans les Hellénides internes: les massifs de l'Othrys et du Pélion (Grèce continentale). Société Géologique du Nord, Publication 8, 2 volumes. (970 pp.).
Florineth, D., Froitzheim, N., 1994. Transition from continental to oceanic basement in the Tasna nappe (Engadin window, Graubünden, Switzerland): evidence for Early Cretaceous opening of the Valais ocean. Schweizerische Mineralogische und Petrographische Mitteilungen 74, 437–448.
Ford, M., Duchêne, S., Gasquet, D., Vanderhaeghe, O., 2006. Two-phase orogenic convergence in the external and internal SW Alps. Journal of the Geological Society of London 161, 815–826.
Frank, W., Schlager, W., 2006. Jurassic strike slip versus subduction in the Eastern Alps. International Journal of Earth Sciences 95 (3), 431–450. doi:10.1007/s00531-005-0045-7.
Frisch, W., 1979. Tectonic progradation and plate tectonic evolution of the Alps. Tectonophysics 60, 121–139.
Frizon de Lamotte, D., Saint Bezar, B., Bracène, R., 2000. The two main steps of the Atlas building and geodynamics of the Western Mediterranean. Tectonics 19 (4), 740–761.
Froitzheim, N., Eberli, G.P., 1990. Extensional detachment faulting in the evolution of a Tethys passive continental margin, Eastern Alps, Switzerland. Geological Society of America Bulletin 102, 1297–1308.
Froitzheim, N., Manatschal, G., 1996. Kinematics of Jurassic rifting, mantle exhumation, and passive-margin formation in the Austroalpine and Penninic nappes (eastern Switzerland). Geological Society of America Bulletin 108 (9), 1120–1133.
Froitzheim, N., Rubatto, D., 1998. Continental breakup by detachment faulting: field evidence and geochronological constraints (Tasna nappe, Switzerland). Terra Nova 10, 171–176.
Froitzheim, N., Schmid, S.M., Conti, P., 1994. Repeated change from crustal shortening to orogen-parallel extension in the Austroalpine units of Graubünden. Eclogae Geologicae Helvetiae 87 (2), 559–612.
Froitzheim, N., Schmid, S.M., Frey, M., 1996. Mesozoic paleogeography and the timing of eclogite-facies metamorphism in the Alps: a working hypothesis. Eclogae Geologicae Helvetiae 89 (1), 81–110.
Froitzheim, N., Janak, M., Kurz, W., 2007. The structure of the Austroalpine napppes and the subduction and exhumation of Pohorje UHP metamorphic rocks. 8th Workshop on Alpine Geological Studies, Davos, Switzerland, p. 19.
Froitzheim, N., Plasienka, D., Schuster, R., 2008. Alpine Tectonics of the Alps and Western Carpathians. In: McCann, T. (Ed.), Mesozoic and Cenozoic. : The Geology of Central Europe, Volume 2. Geological Society, London, pp. 1141–1232.
Fügenschuh, B., Loprieno, A., Ceriani, S., Schmid, S.M., 1999. Structural analyses of the Subbriançonnais and Valais units in the area of Moûtiers (Savoy, Western Alps). Palaeographic and tectonic consequences. International Journal of Earth Sciences 88, 201–218.
Funicello, F., Moroni, M., Piromallo, C., Faccenna, C., Cenedese, A., Bui, H.A., 2006. Mapping mantle flow during retreating subduction: laboratory models analyzed by feature tracking. Journal of Geophysical Research 111, B03402. doi:10.1029/2005JB003792.
Gaupp, R., 1982. Sedimentationsgeschichte und Paläotektonik der kalkalpinen Mittelkreide (Allgäu, Tirol, Vorarlberg). Zitteliana 8, 33–72 (München).
Gawlick, H.-J., Frisch, W., Vecsei, A., Steiger, T., Böhm, F., 1999. The change from rifting to thrusting in the Northern Calcareous Alps as recorded in Jurassic sediments. Geologische Rundschau 87, 644–657.
Giese, P., Reutter, K.-J., Jacobshagen, V., Nicolich, R., 1982. Explosion seismic crustal studies in the Alpine Mediterranean region and their implications for tectonic processes. In: Berckhemer, H., Hsü, K.J. (Eds.), Alpine-Mediterranean Geodynamics. : Geodynamics Series, 7. American Geophysical Union, pp. 39–73.
Goffé, B., Schwartz, S., Lardeaux, J.M., Bousquet, R., 2004. Explanatory notes to the map: metamorphic structure of the Alps. Mitteilungen der Österreichischen Mineralogischen Gesellschaft 149, 125–144.
Gong, Z., van Hinsbergen, D.J.J., Vissers, R.L.M., Dekkers, M.J., 2009. Early Cretaceous syn-rotational extension in the Organyà basin—new constraints on the palinspastic position of Iberia during its rotation. Tectonophysics 473, 312–323.
Gradstein, F.M., Ogg, J.G., Smith, A.G., et al., 2004. A Geologic Time Scale. Cambridge University Press.
Grenerczy, G., Sella, G., Stein, S., Kenyeres, A., 2005. Tectonic implications of the GPS velocity field in the northern Adriatic region. Geophysical Research Letters 32. doi:10.1029/2005GL022947.
Gueydan, F., Le Garzic, E., Carry, N., 2009. P/T ration in high-pressure rocks as a function of dip and velocity of continental subduction. Lithosphere 1 (5), 282–290. doi:10.1130/L46.1.
Haas, J., Pero, S., 2004. Mesozoic evolution of the Tisza Mega-Unit. International Journal of Earth Sciences 93, 297–313.
Hafkenscheid, E., Wortel, M.J.R., Spakman, W., 2006. Subduction history of the Tethyan region derived from seismic tomography and tectonic reconstructions. Journal of Geophysical Research 111, B08401. doi:10.1029/2005/B003791.
Hager, B.H., 1984. Subducted slabs and the geoid: constraints on mantle rheology and flow. Journal of Geophysical Research 89, 6003–6015.
Hammerschmidt, K., Frank, E., 1991. Relics of high-pressure metamorphism in the Lepontine Alps (Switzerland)—40Ar/39Ar and microprobe analyses on white K-micas. Schweizerische Mineralogische und Petrographische Mitteilungen 71, 261–275.
Handy, M.R., 1996. The transition from passive to active margin tectonics: a case study from the zone of Samedan (eastern Switzerland). Geologische Rundschau 85 (4), 832–851.
Handy, M.R., Oberhänsli, R., 2004. Explanatory notes to age map of the metamorphic structure of the Alps—tectonic interpretation and outstanding problems. Mitteilungen der Österreichischen Mineralogischen Gesellschaft 149, 201–226.
Handy, M.R., Zingg, A., 1991. The tectonic and rheological evolution of an attenuated cross section of the continental crust: Ivrea crustal section, Southern Alps, northwestern Italy and southern Switzerland. Geological Society of America Bulletin 103, 236–253.
Handy, M.R., Herwegh, M., Regli, C., 1993. Die Tektonische Entwicklung der westlichen Zone von Samedan (Oberhalbstein, Graubünden). Eclogae Geologicae Helvetiae 86 (3), 785–817.
Handy, M.R., Herwegh, M., Kamber, B., Tietz, R., Villa, I., 1996. Geochronologic, petrologic and kinematic constraints on the evolution of the Err-Platta boundary, part of a fossil continent–ocean suture in the Alps (eastern Switzerland). Schweizerische Mineralogische und Petrographische Mitteilungen 76 (3), 453–474.
Handy, M.R., Franz, L., Heller, F., Janott, B., Zurbriggen, R., 1999. Multistage accretion and exhumation of the continental crust (Ivrea crustal section, Italy and Switzerland). Tectonics 18 (6), 1154–1177.
Handy, M.R., Babist, J., Wagner, R., Rosenberg, C.L., Konrad-Schmolke, M., 2005. Decoupling and its relation to strain partitioning in continental lithosphere: insight from the Periadriatic fault system (European Alps). In: Gapais, D., Brun, J.-P., Cobbold, P.R. (Eds.), Deformation Mechanisms, Rheology and Tectonics: from Minerals to the Lithosphere: Geological Society, London, Special Publications, 243, pp. 249–276.
Harland, W.B., Cox, A.V., Llewellyn, P.G., Pickton, C.A.G., Smith, A.G., Walters, R., 1989. A Geologic Time Scale. Cambridge University Press, Cambridge, U.K.
Haug, E., 1908–1911. Traité de Géologie. Ii. Les Périodes géologiques. Armand Colin, Paris, pp. 539–2024.
Husson, L., 2006. Dynamic topography above retreating subduction zones. Geology 34 (9), 741–744. doi:10.1130/G22436.1.
Jolivet, L., Faccenna, C., 2000. Mediterranean extension and the Africa–Eurasia collision. Tectonics 19, 1095–1106.
Jolivet, L., Faccenna, C., Goffé, B., Burov, E., Agard, P., 2003. Subduction tectonics and exhumation of high-pressure metamorphic rocks in the Mediterranean orogens. American Journal of Science 303, 353–409.
Kastens, K., Mascle, J., et al., 1988. ODP Leg 17 in the Tyrrhenian Sea: insights into passive margin and backarc basin evolution. Geological Society of America Bulletin 100, 1140–1156.
Kelts, K., 1981. A comparison of some aspects of sedimentation and translational tectonics in the Gulf of California and the Mesozoic Tethys. Eclogae Geologicae Helvetiae 74, 317–338.
Kissling, E., 1984. Three-dimensional gravity model of the northern Ivrea-Verbano Zone. In: Wagner, J.-J., St. Müller (Eds.), Geomagnetic and Gravimetric Studies of the Ivrea Zone: Matér. Géol. Suisse. Géophys., 21, pp. 55–61.
Kissling, E., 2008. Deep structure and tectonics of the Valais—and the rest of the Alps. Bulletin Angewandte Geologie 13 (2), 3–10.
Kissling, E., Schmid, S.M., Lippitsch, R., Ansorge, J., Fügenschuh, B., 2006. Lithosphere structure and tectonic evolution of the Alpine arc: new evidence from high-resolution teleseismic tomography. In: Gee, D., Stephenson, R.A. (Eds.), European Lithosphere Dynamics: Geological Society, London, Memoirs, 32, pp. 129–145.
Konrad-Schmolke, M., Babist, J., Handy, M.R., O'Brien, P.J., 2006. The physico-chemical properties of a subducted slab from garnet zonation patterns (Sesia Zone, Western Alps). Journal of Petrology 47 (11), 2123–2148.
Kozur, H., Mostler, H., 1992. Erster paläontologischer Nachweis von Meliaticum und Südrudabanyaicum in den Nördlichen Kalkalpen (Österreich) und ihre Beziehungen zu den Abfolgen in den Westkarpaten. Geologisch-Paläontologische Mitteilungen Innsbruck 18, 87–129.
Kurz, W., Handler, R., Bertoldi, C., 2008. Tracing the exhumation of the Eclogite Zone (Tauern Window, Eastern Alps) by 40Ar/39Ar dating of white mica in eclogites. Swiss Journal of Geosciences 101 (Supplement 1), 191–206.
Lagabrielle, Y., Bodinier, J.L., 2008. Submarine reworking of exhumed subcontinental mantle rocks: field evidence from the Lherz peridotites, French Pyrenees. Terra Nova 20, 11–21.
Lahondère, D., Guerrot, C., 1997. Datation Sm–Nd du métamorphisme éclogitique en Corse alpine: un argument pour l'existence au Crétacé supérieur d'une zone de subduction active localisée sous le bloc corso-sarde. Géologie de la France 3, 3–11.
Lanphere, M., Coleman, R.G., Karamata, S., Pamić, J., 1975. Age of amphibolites associated with Alpine peridotites in the Dinaride ophiolite zone, Yugoslavia. Earth and Planetary Science Letters 26, 271–276.
Lapen, T.J., Johnson, C.M., Baumgartner, L.P., Mahlen, N.J., Beard, B.L., Amato, J.M., 2003. Burial rates during prograde metamorphism of an ultra-high-pressure terrane: an example from Lago di Cignana, western Alps, Italy. Earth and Planetary Sciences 681, 1–16.
Laubscher, H.-P., 1970. Bewegung und Wärme in der alpinen Orogenese. Schweizerische Mineralogische und Petrographische Mitteilungen 50 (3), 565–596.
Laubscher, H.P., 1971. Das Alpen-Dinariden Problem und die Palinspastik der südlichen Tethys. Geologische Rundschau 60, 813–833.
Laubscher, H.-P., 1975. Plate boundaries and microplates in Alpine history. American Journal of Science 275, 865–876.
Laubscher, H.-P., 1991. The arc of the Western Alps today. Eclogae Geologicae Helvetiae 84 (3), 631–659.
Laubscher, H.-P., Bernoulli, D., 1977. Mediterranean and Tethys. In: Nairn, A.E.M., Kanes, W.H., Stehli, F.G. (Eds.), The Ocean Basins and Margins, 4A. Plenum Publishing Corp., pp. 1–28.
Laubscher, H.P., Biella, G.C., Cassinis, R., Gelati, R., Lozej, A., Scarascia, S., Tabacco, I., 1992. The collisional knot in Liguria. Geologische Rundschau 81, 275–289.
Lavier, L.L., Manatschal, G., 2006. A mechanism to thin the continental lithosphere at magma-poor margins. Nature 440. doi:10.1038/nature04608.
Le Pichon, X., 1968. Sea-floor spreading and continental drift. Journal of Geophysical Research 73, 3661–3697.
Lemoine, M., Tricart, P., Boillot, G., 1987. Ultramafic and gabbroic ocean floor of the Ligurian Tethys (Alps, Corsica, Apennines): in search of a genetic model. Geology 15, 622–625.

Liati, A., Gebauer, D., Fanning, M., 2003a. The youngest basic ocean magmatism in the Alps (Late Cretaceous; Chiavenna unit, Central Alps): geochronological constraints and geodynamic significance. Contributions to Mineralogy and Petrology 146, 144–158. doi:10.1007/s00410-003-0485-7.

Liati, D., Gebauer, D., Froitzheim, N., Fanning, M., 2003b. Origin and geodynamic significance of metabasic rocks from the Antrona ophiolites (Western Alps): new insights from SHRIMP-dating. Geophysical Research Abstracts 5, 12648.

Liniger, M., Nievergelt, P., 1990. Stockwerk-Tektonik im südlichen Graubünden. Schweizerische Mineralogische und Petrographische Mitteilungen 70, 95–101.

Lippitsch, R., Kissling, E., Ansorge, J., 2003. Upper mantle structure beneath the Alpine orogen from high-resolution teleseismic tomography. Journal of Geophysical Research 108 (B8), 2376. doi:10.1029/2002JB002016.

Lombardi, D., Braunmiller, J., Kissling, E., Giardini, D., 2009. Alpine mantle transition zone imaged by receiver functions. Earth and Planetary Science Letters 278, 163–174.

Lombardo, B., Rubatto, D., Castelli, D., 2002. Ion microprobe U–Pb dating of zircon from a Monviso metaplagiogranite: implications for the evolution of the Piedmont-Liguria Tethys in the Western Alps. Ofioliti 27, 109–117.

Lonergan, L., 1993. Timing and kinematics of deformation in the Malaguide Complex, Internal Zone of the Betic Cordillera, Southeast Spain. Tectonics 12, 460–476.

Loprieno, A. 2001. A combined structural and sedimentological approach to decipher the evolution of the Valais domain in Savoy, Western Alps. Unpublished Ph.D. thesis, University Basel, Switzerland, 304 pp.

Macera, P., Gasperini, D., Piromallo, C., Blichert-Toft, J., Bosch, D., Del Moro, A., Martin, S., 2003. Geodynamic implications of deep-mantle upwelling in the source of Tertiary volcanics from the Veneto region (South-Eastern Alps). Journal of Geodynamics 36, 563–590.

Mahlen, N.L., Johnson, C.M., Baumgartner, L.P., Beard, B.L., 2005. Provenance of Jurassic Tethyan sediments in the HP/UHP Zermatt-Saas ophiolite, western Alps. Geological Society of America Bulletin 117 (3/4), 530–544.

Malavieille, J., Lacassin, R., Mattauer, M., 1984. Tectonic significance of stretching lineations in the Western Alps. Bulletin de la Societé Géologique de France 26 (5), 895–906.

Malavieille, J., Chemenda, A., Larroque, Ch., 1998. Evolutionary model for Alpine Corsica: mechanism for ophiolite emplacement and exhumation of high-pressure rocks. Terra Nova 10, 317–322.

Malinverno, A., Ryan, W.B.F., 1986. Extension in the Tyrrhenian sea and shortening in the Apennines as results of arc migration driven by sinking of the lithosphere. Tectonics 5, 227–245.

Malusa, M.G., Polino, R., Zattin, M., Bigazzi, G., Martin, S., Piana, F., 2005. Miocene to Present differential exhumation in the Western Alps: insights from fission track thermochronology. Tectonics 24, TC3004. doi:10.1029/2004TC001782.

Manatschal, G., Bernoulli, D., 1999. Architecture and tectonic evolution of nonvolcanic margins: present-day Galicia and ancient Adria. Tectonics 18, 1099–1119.

Manatschal, G., Müntener, O., 2009. A type-sequence across an ancient magma-poor ocean–continent transition: the example of the western Alpine Tethys ophiolites. Tectonophysics 473 (1–2), 4–19. doi:10.1016/j.tecto.2008.07.021.

Manatschal, G., Engström, A., Desmurs, L., Schaltegger, U., Cosca, M., Müntener, O., Bernoulli, D., 2006. What is the tectono-metamorphic evolution of continental break-up? The example of the Tasna Ocean–Continent Transition. Journal of Structural Geology 28, 1849–1869.

Mandl, G., 2000. The Alpine Sector of the Tethyan shelf—Examples of Triassic to Jurassic sedimentation and deformation from the Northern Calcareous Alps. Mitteilungen der Österreichischen Geologischen Gesellschaft 92, 61–77.

Mandl, G., Ondrejicka, A., 1991. Über eine triadische Tiefwasserfazies (Radiolarite, Tonschiefer) in den nördlichen Kalkalpen-ein Vorbericht. Jahrbuch der Geologischen Bundesanstalt 134 (2), 309–318.

Mandl, G., Ondrejicka, A., 1993. Radiolarite und Conodonten aus dem Meliatikum im Ostabschnitt der NKA. Jahrbuch der Geologischen Bundesanstalt 136 (4), 841–871.

Marroni, M., Molli, G., Ottria, D., Pandolfi, L., 2001. Tectono-sedimentary evolution of the External Liguride units (Northern Apennine, Italy): insights in the pre-collisional history of a fossil ocean–continent transition zone. Geodinamica Acta 14, 307–320.

Márton, E., Zampieri, D., Grandesso, P., Ćosović, V., Moro, A., 2010. New Cretaceous paleomagnetic results from the foreland of the Southern Alps and the refined apparent polar wander path for stable Adria. Tectonophysics 480, 57–72.

Matter, A., Homewood, P., Caron, C., Rigassi, D., van Stuijvenberg, J., Weidmann, M., Winkler, W., 1980. Flysch and Molasse of Western and Central Switzerland. Excursion No. V. In: Aubert, D., et al. (Ed.), Geology of Switzerland—A Guide Book, Part B: Geological Excursions. Wepf and Co. Publishers, Basel, pp. 261–293.

Mayer, A., Cortiana, G., Dal Piaz, G.V., Deloule, E., De Pieri, R., Jobstraibitzer, P., 2003. U–Pb single zircon ages of the Adamello batholith, Southern Alps. Memorie di Scienze Geologiche (Padova) 55, 151–167.

Michard, A., Chalouan, A., Feinberg, H., Goffé, B., Montigny, R., 2002. How does the Alpine belt end between Spain and Morocco? Bulletin. Société Géologique de France 173, 3–15.

Michard, A., Negro, F., Saddiqi, O., Bouybaouene, M.L., Chalouan, A., Montigny, R., Goffé, B., 2006. Pressure–temperature–time constraints on the Maghrebide mountain building: evidence from the Rif-Betic transect (Marocco, Spain), Algerian correlations, and geodynamic implications. Comptes Rendus Geoscience 338, 92–114.

Milnes, A.G., 1978. Structural zones and continental collision, Central Alps. Tectonophysics 47, 369–392.

Molli, G., 2008. Northern Apennine–Corsica orogenic system: an updated view. In: Siegesmund, S., Fügenschuh, B., Froitzheim, N. (Eds.), Tectonic Aspects of the Alpine–Dinaride–Carpathian System: Geological Society, London, Special Publication, 298, pp. 413–442.

Morag, N., Avigad, D., Harlavan, Y., McWilliams, M.O., Michard, A., 2008. Rapid exhumation and mountain building in the Western Alps: petrology and 40Ar/39Ar geochronology of detritus from Tertiary basins of southwestern France. Tectonics 27, TC2004. doi:10.1029/2007TC002142.

Müntener, O., Rubatto, D., Kaczmarek, M.-A., Gregory, C., Barnhoorn, A., 2007. From igneous formation to high-pressure recrystallization: the record of zircon and allanite from the Lanzo massif (N-Italy). 8th Workshop on Alpine Geological Studies, Davos, Switzerland, pp. 51–52.

Mutti, E., Bernoulli, D., Lucchi, F.R., Tinteri, R., 2009. Turbidites and turbidity currents from Alpine 'flysch' to the exploration of continental margins. Sedimentology 56, 267–318.

Nagel, T.J., 2008. Subduction, collision and exhumation recorded in the Adula nappe, central Alps. In: Siegesmund, S., Fügenschuh, B., Froitzheim, N. (Eds.), Tectonic Aspects of the Alpine–Dinarides–Carpathian System: Geological Society, London, Special Publications, 298, pp. 365–392.

Neubauer, F., Dallmeyer, R.D., Dunkl, I., Schirnik, D., 1995. Late Cretaceous exhumation of the metamorphic Gleinalm dome, Eastern Alps: kinematics, cooling history and sedimentary response in a sinistral wrench corridor. Tectonophysics 242, 79–98.

Nocquet, J.-M., Calais, E., 2004. Geodetic measurements of crustal deformation in the Western Mediterranean and Europe. Pure and Applied Geophysics 161, 661–681. doi:10.1007/s00024-003-2468-z.

Oberhänsli, R. Bousquet, R., Engi, M., Goffé, B., Gosso, G., Handy, M.R., Höck, V., Koller, F., Lardeaux, J.-M., Polino, R., Rossi, Ph., Schuster, R., Schwartz, St., Spalla, I. 2004: Metamorphic structure of the Alps. Scale 1:1.000.000, Commission for the Geological Map of the World, Paris.

Oberhauser, R., 1983. Mikrofossilfunde im Nordwestteil des Unterngadiner Fensters sowie im Verspalaflysch des Rätikon. Jahrbuch der Geologischen Bundesanstalt, Wien 126, 71–93.

Oberhauser, R., 1995. Zur Kenntnis der Tektonik und der Paläogeographie des Ostalpenraumes zur Kreide-, Paleozän-, und Eozänzeit. Jahrbuch der Geologischen Bundesanstalt 138 (2), 369–432.

Olivet, J.-L., 1996. La Cinématique de la Plaque Ibérique. Bulletin des Centres de Recherches Exploration-Production Elf-Aquitaine 20 (1), 131–195.

Ortner, H., 1994. Die Muttekopfgosau (Lechtaler Alpen, Tirol, Österreich): Sedimentologie und Beckenentwicklung. Geologische Rundschau 83, 197–211.

Ortner, H., 2001. Growing folds and sedimentation of the Gosau Group, Muttekopf, Northern Calcareous Alps, Austria. International Journal of Earth Sciences 90, 727–739.

Pamić, J., 2002. The Sava-Vardar Zone of the Dinarides and Hellenides versus the Vardar Ocean. Eclogae Geologicae Helvetiae 95, 99–113.

Pamić, J., Tomljenović, B., Balen, D., 2002. Geodynamic and petrogenetic evolution of Alpine ophiolites from the central and NW Dinarides: an overview. Lithos 65, 113–142.

Parsons, B., Sclater, J.G., 1977. An analysis of the variation of ocean floor bathymetry and heat flow with age. Journal of Geophysical Research 82, 803–827.

Peresson, H., Decker, K., 1997. The Tertiary dynamics of the northern Eastern Alps (Austria): changing palaeostresses in a collisional plate boundary. Tectonophysics 272, 125–157.

Philippot, P., 1990. Opposite vergence of nappes and crustal extension in the French–Italian Western Alps. Tectonics 9 (5), 1143–1164.

Piromallo, C., Faccenna, C., 2004. How deep can we find traces of Alpine subduction? Geophysical Research Letters 31. doi:10.1029/2003GL019288.

Piromallo, C., Morelli, A., 2003. P-wave tomography of the mantle under the Alpine–Mediterranean area. Journal of Geophysical Research 108 (B2). doi:10.1029/2002JB001757.

Piromallo, C., Becker, T.W., Funicello, F., Faccenna, C., 2006. Three-dimensional instantaneous mantle flow induced by subduction. Geophysical Research Letters 31, L06605. doi:10.1029/2003GL019288.

Platt, J.P., 2007. From orogenic hinterlands to Mediterranean-style backarc basins: a comparative analysis. Journal of the Geological Society 164, 297–311.

Platt, J.P., Kelley, S.P., Carter, A., Orozco, M., 2005. Timing of tectonic events in the Alpujárride Complex, Betic Cordillera, southern Spain. Journal of the Geological Society 162, 451–462.

Platt, J.P., Anczkiewicz, R., Soto, J.-I., Kelley, S.P., Thirwall, M., 2006. Early Miocene continental subduction and rapid exhumation in the western Mediterranean. Geology 34 (11), 981–984.

Pleuger, J., Nagel, T.J., Walter, J.M., Jansen, E., Froitzheim, N., 2008. On the role and importance of orogen-parallel and -perpendicular extension, transcurrent shearing, and backthrusting in the Monte Rosa nappe and the Southern Steep Belt of the Alps (Pennine zone, Switzerland and Italy). In: Siegesmund, S., Fügenschuh, B., Froitzheim, N. (Eds.), Tectonic Aspects of the Alpine–Dinaride–Carpathian System: Geological Society, London, Special Publication, 298, pp. 251–280.

Puga, E., Diaz De Federico, A., Nieto, J.M., 2002. Tectonostratigraphic subdivision and petrological characterisation of the deepest complexes of the Betic zone: a review. Geodinamica Acta 15, 23–43.

Puga, E., Díaz de Federico, A., Nieto, J.M., Díaz Puga, M.A., Rodríguez Martínez-Conde, J.A., 2009. The Betic Ophiolitic Association: a very significant Geological Heritage that needs to be preserved. Geoheritage 1, 11–31.

Ratschbacher, L., Neubauer, F., Schmid, S.M., Neugebauer, J., 1989. Extension in compressional orogenic belts: the Eastern Alps. Geology 17, 404–407.

Ratschbacher, L., Frisch, W., Linzer, H.-G., Merle, O., 1991. Lateral extrusion in the Eastern Alps, part 2: structural analysis. Tectonics 10 (2), 257–271.

Ricou, L.E., Siddans, A.W.B., 1986. Collision tectonics in the western Alps. In: Coward, M.P., Dietrich, D., Park, P.G. (Eds.), Continent–Continent Collision: Himalayan-Alpine Belt: Geological Society, London, Special Publications, 19, pp. 229–244. doi:10.1144/GSL.SP.1986.019.01.13.

Ring, U., Ratschbacher, L., Frisch, W., Biehler, D., Kralik, M., 1989. Kinematics of the Alpine plate-margin: structural styles, strain and motion along the Penninic–

Austroalpine boundary in the Swiss–Austrian Alps. Journal of the Geological Society 146, 835–849.

Roca, E., Frizon de Lamotte, D., Mauffret, A., Bracène, R., Vergés, J., Benaouali, N., Fernandez, M., Munoz, J.A., Zeyen, H., 2004. TRANSMED Transect II: Aquitaine Basin–Pyrenees–Ebro Basin–Catalan Coastal Ranges–Valencia Trough–Balearic Promontory–Algerian Basin–Kabylies–Atlas–Saharan Domain. In: Cavazza, W., Roure, F., Spakman, W., Stampfli, G.M., Ziegler, P.A. (Eds.), The TRANSMED Atlas: The Mediterranean Region from Crust to Mantle. Springer Verlag.

Roesli, F., 1944. Sedimentäre Zone von Samedan. Eclogae Geologicae Helvetiae 37 (2), 355–383.

Rosenbaum, G., Lister, G.S., Duboz, C., 2002a. Relative motions of Africa, Iberia and Europe during Alpine orogeny. Tectonophysics 359, 117–129.

Rosenbaum, G., Lister, G.S., Duboz, C., 2002b. Reconstruction of the tectonic evolution of the western Mediterranean since the Oligocene. In: Rosenbaum, G., Lister, G.S. (Eds.), Reconstruction of the Evolution of the Alpine-Himalayan Orogen: Journal of the Virtual Explorer, 8, pp. 107–126 (2002).

Rosenbaum, G., Lister, G.S., Duboz, C., 2004. The Mesozoic and Cenozoic motion of Adria (central Mediterranean): a review of constraints and limitations. Geodinamica Acta 17 (2), 125–139.

Royden, L.H., 1993. Evolution of retreating subduction boundaries formed during continental collision. Tectonics 12, 629–638.

Royden, L.H., Husson, L., 2006. Trench motion, slab geometry and viscous stresses in subduction systems. Geophysical Journal International 167 (2), 881–905. doi:10.1111/j.1365-246X.2006.03079.x.

Royer, J.-Y., Müller, R.D., Gahagan, L.M., Lawver, L.A., Mayes, C.L., Nürnberg, D., Sclater, J.G., 1992. A global isochron chart. University of Texas Institute for Geophysics Technical Report, 117, p. 117.

Rubatto, D., Hermann, J., 2001. Exhumation as fast as subduction? Geology 29 (1), 3–6.

Rubatto, D., Hermann, J., 2003. Zircon formation during fluid circulation in eclogites (Monviso, Western Alps): implications for Zr and Hf budget in subduction zones. Geochimica et Cosmochimica Acta 67, 2173–2187.

Rubatto, D., Hermann, J., 2006. Geochronological constraints on fast exhumation: the example of the Central Alps. Goldschmidt Conference, p. A543. doi:10.1016/j.gca.2006.06.1001.

Rubatto, D., Gebauer, D., Fanning, M., 1998. Jurassic formation and Eocene subduction of the Zermatt-Saas-Fee ophiolites: implications for the geodynamic evolution of the Central and Western Alps. Contributions to Mineralogy and Petrology 132, 269–287.

Rubatto, D., Gebauer, D., Compagnoni, R., 1999. Dating of eclogite-facies zircons. The age of the Alpine metamorphism in the Sesia-Lanzo Zone (Western Alps). Earth and Planetary Science Letters 167, 141–158.

Savostin, L.A., Sibuet, J.-C., Zonenshain, L.P., Le Pichon, X., Roulet, M.-J., 1986. Kinematic evolution of the Tethys belt from the Atlantic ocean to the Pamir since the Triassic. Tectonophysics 123, 1–35.

Schaltegger, U., Desmurs, L., Manatschal, G., Müntener, O., Meier, M., Frank, M., Bernoulli, D., 2002. Transition from a rifted continental margin to a slow spreading system: field and isotopic constraints from a Tethyan ophiolite. Terra Nova 14, 156–162.

Schertl, H.-P., Schreyer, W., Chopin, C., 1991. The pyrope-coesite rocks and their country rocks at Parigi, Dora Maira Massif, Western Alps: detailed petrography, mineral chemistry and PT-path. Contributions to Mineralogy and Petrology 108, 1–21.

Schmid, S.M., 1993. Ivrea Zone and Adjacent Southern Alpine Basement. In: von Raumer, J.F., Neubauer, F. (Eds.), Pre-Mesozoic Geology in the Alps. Springer Verlag, Berlin, pp. 567–584.

Schmid, S.M., Kissling, E., 2000. The arc of the western Alps in the light of geophysical data on deep crustal structure. Tectonics 19 (1), 62–85.

Schmid, S.M., Aebli, H.R., Heller, F., Zingg, A., 1989. The role of the Periadriatic Line in the tectonic evolution of the Alps. In: Coward, M.P., Dietrich, D., R.G., Park (Eds.), Alpine Tectonics. : Geological Society, London, Special Publications, 45. Blackwell, London, pp. 153–171.

Schmid, S.M., Rück, P., Schreurs, G., 1990. The significance of the Schams nappe for the reconstruction of the paleotectonic and orogenic evolution of the Penninic zone along the NFP-20 East traverse (Grisons, eastern Switzerland). In: Roure, F., Heitzmann, P., Polino, R. (Eds.), Deep Structure of the Alps: Mémoires de la Société Géologique de France, 156, pp. 263–287.

Schmid, S.M., Pfiffner, O.A., Froitzheim, N., Schönborn, G., Kissling, E., 1996. Geophysical–geological transect and tectonic evolution of the Swiss–Italian Alps. Tectonics 15 (5), 1036–1064.

Schmid, S.M., Pfiffner, O.A., Schreurs, G., 1997. Rifting and collision in the Penninic zone of eastern Switzerland. In: Pfiffner, A.O., Lehner, P., Heitzmann, P., St. Mueller, Steck, A. (Eds.), Deep Structure of the Swiss Alps: Results from the NRP 20. Birkhäuser Verlag, Basel, pp. 60–185.

Schmid, S.M., Fügenschuh, B., Kissling, E., Schuster, R., 2004a. Tectonic Map and overall architecture of the Alpine orogen. Eclogae Geologicae Helvetiae 97 (1), 93–117.

Schmid, S.M., Fügenschuh, B., Kissling, E., Schuster, R., 2004b. TRANSMED transects IV, V and VI: three lithospheric transects across the Alps and their forelands. CD. In: Cavazza, W., Roure, F., Spakman, W., Stampfli, G.M., Ziegler, P.A. (Eds.), The Transmed Atlas: The Mediterranean Region from Crust to Mantle. Springer, Berlin.

Schmid, S.M., Bernoulli, D., Fügenschuh, B., Matenco, L., Schefer, S., Schuster, R., Tischler, M., Ustaszewski, K., 2008. The Alpine–Carpathian–Dinaridic orogenic system: correlation and evolution of tectonic units. Swiss Journal of Geosciences 101 (1), 139–183.

Schönborn, G., 1992. Alpine tectonics and kinematic models of the Central Southern Alps. Memorie di Scienze Geologiche dell' Università di Padova 44, 229–393.

Schuster, R., 2003. Das eo-Alpidische Ereignis in den Ostalpen: Plattentektonische Situation und interne Struktur des Ostalpinen Kristallins. Arbeitstagung der Geologischen Bundesanstalt, Blatt 148 "Brenner", 2003, Verlag der Geologischen Bundesanstalt, Wien, pp. 141–159.

Schuster, R., Stüwe, K., 2008. Permian metamorphic event in the Alps. Geology 36, 603–606.

Schuster, R., Thöni, M., 1996. Permian garnets: indication for a regional Permian metamorphism in the Southern part of the Austroalpine basement units. Mitteilungen der Österreichischen Geologischen Gesellschaft 141, 219–221.

Schuster, R., Koller, F., Hoeck, V., Hoinkes, G., Bousquet, R., 2004. Explanatory notes to age map of the metamorphic structure of the Alps—metamorphic evolution of the Eastern Alps. Mitteilungen der Österreichischen Mineralogischen Gesellschaft 149, 175–199.

Schwartz, S., Lardeaux, J.M., Tricart, P., Guillot, S., Labrin, E., 2007. Diachronous exhumation of HP–LT metamorphic rocks from south-western Alps: evidence from fission-track analysis. Terra Nova 19, 133–140.

Schwizer, B., 1984. Die Tristel-Formation. Vergleichende Untersuchungen in Graubünden, Liechtenstein, Vorarlberg und Bayern. PhD. Thesis, Univ. of Bern, 185 pp.

Sengör, A.M.C., 1979. Mid-Mesozoic closure of Permo-Triassic Tethys and its implications. Nature 279, 590–593.

Séranne, M., 1999. The Gulf of Lion continental margin (NW Mediterranean) revisited by IBS: an overview. In: Durand, B., Jolivet, L., Horvath, F., Séranne, M. (Eds.), The Mediterranean Basins: Tertiary Extension within the Alpine Orogen: Geological Society, London, Special Publications, 156, pp. 15–36.

Sibuet, J.-C., Srivastava, S.P., Spakman, W., 2004. Pyrenean orogeny and plate kinematics. Journal of Geophysical Research 109, B08104. doi:10.1029/2003JB002514.

Sinclair, H.D., 1997. Tectonostratigraphic model for underfilled peripheral foreland basins: an Alpine perspective. Geological Society of America Bulletin 109 (3), 324–346.

Sloman, L.E., 1989. Triassic shoshonites from the Dolomites, northern Italy: alkaline rocks in a strike-slip setting. Journal of Geophysical Research 94 (B4), 4655–4666.

Spakman, W., Wortel, M.J.R., 2004. A tomographic view on Western Mediterranean geodynamics. Chapter 2. In: Cavazza, W., Roure, F.M., Stampfli, G.M., Ziegler, P.A. (Eds.), The Transmed Atlas—The Mediterranean Region from Crust to Mantle. Springer, Berlin, pp. 31–52.

Spakman, W., van der Lee, S., van der Hilst, R., 1993. Traveltime tomography of the European–Mediterranean mantle down to 1400 km. Physics of the Earth and Planetary Interiors 79, 3–74.

Srivastava, S.P., Roest, W.R., Kovacs, L.C., Oakay, G., Lévesque, S., Verhoef, J., Macnab, R., 1990. Motion of Iberia since the Late Jurassic. Results from detailed aeromagnetic measurements in the Newfoundland Basin. Tectonophysics 184, 229–260.

Stampfli, G.M., 1994. Exotic terrains in the Alps: a solution for a single Jurassic ocean. Schweizerische Mineralogische und Petrographische Mitteilungen 74, 449–452.

Stampfli, G.M., Borel, G.D., 2002. A plate tectonic model for the Paleozoic and Mesozoic constrained by dynamic plate boundaries and restored synthetic oceanic isochrons. Earth and Planetary Science Letters 196, 17–33.

Stampfli, G.M., Borel, G.D., 2004. The TRANSMED transects in space and time: constraints on the paleotectonic evolution of the Mediterranean domain. Chapter 3. In: Cavazza, W., Roure, F.M., Stampfli, G.M., Ziegler, P.A. (Eds.), The Transmed Atlas—The Mediterranean region from crust to mantle. Springer, Berlin, pp. 53–80.

Stampfli, G.M., Mosar, J., Marquer, D., Marchant, R., Baudin, T., Borel, G., 1998. Subduction and obduction processes in the Swiss Alps. Tectonophysics 296, 159–204.

Steinmann, G., 1905. Die Schardt´sche Überfaltungstheorie und die geologische Bedeutung der Tiefseeabsätze und der ophiolitischen Massengesteine. Berichte der Naturforschende Gesellschaft, Freiburg im Breisgau 16, 18–67.

Steinmann, M., 1994. Ein Beckenmodell für das Nordpenninikum der Ostschweiz. Jahrbuch der Geologischen Bundesanstalt 137 (4), 675–721.

Stüwe, K., Schuster, R., 2010. Initiation of subduction in the Alps: continent or ocean? Geology 38, 175–178.

Sue, C., Tricart, P., 2003. Neogene to ongoing normal faulting in the inner western Alps: a major evolution of the late alpine tectonics. Tectonics 22 (5), 1050. doi:10.1029/2002TC001426.

Suess, E., 1888. Die Entstehung der Meere. Deutsch. Zeitung, 4. Januar 1888, No. 5751, Wien: Beilage.

Suess, E., 1893. Are great ocean depths permanent? Natural Science 2, 180–187.

Thöni, M., 1986. The Rb–Sr thin slab isochron method—an unreliable geochronological method for dating geologic events in polymetamorphic terrains? Memorie di Scienze Geologiche dell' Università di Padova 38, 283–352.

Thöni, M., 2006. Dating eclogite-facies metamorphism in the Eastern Alps—approaches, results, interpretations: a review. Mineralogy and Petrology 88, 123–148.

Thöni, M., Jagoutz, E., 1992. Some new aspects of dating eclogites in orogenic belts: Sm–Nd, Rb–Sr, and Pb–Pb isotopic results from the Austroalpine Saualpe and Koralpe type-locality (Carinthia/Styria, southeastern Austria). Geochimica et Cosmochimica Acta 56, 347–368.

Thöni, M., Miller, J.A., 1987. 40Ar–39Ar and Rb–Sr results from the Austroalpine sheet. Terra Cognita 7, 93.

Thöni, M., Miller, C., Blichert-Toft, J., Whitehouse, M.J., Konzett, J., Zanetti, A., 2008. Timing of high-pressure metamorphism and exhumation of the eclogite type locality (Kupplerbrunn-Prickler Halt, Saualpe, south-eastern Austria): constraints from correlations of the Sm–Nd, Lu–Hf, U–Pb and Rb–Sr isotopic systems. Journal of Metamorphic Geology 26 (5), 561–581.

Tilton, G.R., Schreyer, W., Schertl, H.P., 1991. Pb–Sr–Nd isotopic behaviour of deeply subducted crustal rocks from the Dora Maira massif, Western Alps, Italy: II. What is the age of the ultrahigh-pressure metamorphism? Contributions to Mineralogy and Petrology 108, 22–33.

Tomljenovic, B., 2002. Strukturne Znacajke Medvednice i Samoborskoj gorja. PhD thesis, Univ. Zagreb, Croatia, 208 pp.

Tomljenovic, B., Csontos, L., Márton, E., Márton, P., 2008. Tectonic evolution of the northwestern Internal Dinarides as constrained by structures and rotation of Medvednica Mountains, North Croatia. Geological Society of London. Special Publication 298, 145–167.
Torsvik, T.H., Dietmar Müller, R., Van der Voo, R., Steinberger, B., Gaina, C., 2008. Global plate motion frames: toward a unified model. Reviews of Geophysics 46 (RG3004/2008).
Trommsdorff, V., Dietrich, V., Flisch, M., Stille, P., Ulmer, P., 1990. Mid-Cretaceous, primitive alkaline magmatism in the Northern Calcareous Alps: significance for Austroalpine Geodynamics. Geologische Rundschau 79, 85–97.
Trommsdorff, V., Lopez Sanchez-Vizcaino, V., Gomez-Pugnaire, M.T., Müntener, O., 1998. High pressure breakdown of antigorite to spinifex-textured olivine and orthopyroxene, SE Spain. Contributions to Mineralogy and Petrology 132, 139–148.
Trullenque, G. 2005. Tectonic and microfabric studies along the Penninic Front between Pelvoux and Argentera massifs (Western Alps, France). PhD Thesis, University of Basel, available under http://pages.unibas.ch/diss/2005/DissB_7368.htm.
Trümpy, R., 1976. Du Pèlerin aux Pyrénées. Eclogae Geologicae Helvetiae 69 (2), 249–264.
Trümpy, R., 1980. Geology of Switzerland. A Guide Book. Part A: An Outline of the Geology of Switzerland. Wepf and Co. Publishers, Basel. (104 pp.).
Trümpy, R., 2006. Geologie der Iberger Klippen und ihrer Flysch-Unterlage. Eclogae Geologicae Helvetiae 99 (1), 79–121. doi:10.1007/s00015-006-1180-2.
Ustaszewski, K., Schmid, S.M., Fügenschuh, B., Tischler, M., Kissling, E., Spakman, W., 2008. A map-view restoration of the Alpine–Carpathian–Dinaridic system for the Early Miocene. Swiss Journal of Geosciences 101 (1), 273–294. doi:10.1007/s00015-008-1288-7.
Ustaszewski, K., Schmid, S.M., Lugović, B., Schuster, R., Schaltegger, U., Bernoulli, D., Hottinger, L., Kounov, A., Fügenschuh, B., Schefer, S., 2009. Late Cretaceous intra-oceanic magmatism in the internal Dinarides (northern Bosnia and Herzegovina): implications for the collision of the Adriatic and European plates. Lithos 108, 106–125.
van der Meer, D.G., Spakman, W., van Hinsbergen, D.J.J., Amaru, M.L., Torsvik, T.H., 2009. Towards absolute plate motions constrained by lower-mantle slab remnants. Nature Geoscience 3, 36–39. doi:10.1038/NGEO708.
Vernon, A.J., van der Beek, P.A., Sinclair, H.D., Rahn, M.K., 2008. Increase in late Neogene denudation of the European Alps confirmed by analysis of a fission-track thermochronology database. Earth and Planetary Science Letters 270, 316–329.
Vignaroli, G., Faccenna, C., Jolivet, L., Piromallo, C., Rossetti, F., 2008. Subduction polarity reversal at the junction between the Western Alps and the Northern Apennines, Italy. Tectonophysics 450, 34–50.
von Blanckenburg, F., 1992. Combined high-precision chronometry and geochemical tracing using accessory minerals: applied to the Central-Alpine Bergell intrusion (central Europe). Chemical Geology 100, 19–40.
von Blanckenburg, F., Davies, J.H., 1995. Slab breakoff: a model for syncollisional magmatism and tectonics in the Alps. Tectonics 14 (1), 120–131.
von Eynatten, H., Gaupp, R., 1999. Provenance of Cretaceous sedimentary rocks of the Eastern Alps: evidence for Variscan high-pressure metamorphism and implications for Alpine orogeny. Geology 24, 691–694.
Vrabec, M., Pavlovcic Preseren, P., Stopar, B., 2006. GPS study (1996–2002) of active deformation along the Periadriatic fault system in northeastern Slovenia: tectonic model. Geologica Carpathica 57 (1), 57–65.
Vuichard, J.P., 1989. La marge Austroalpine durant la collision Alpine: evolution tectonometamorphique de la Zone Sesia-Lanzo. Mémoires et Documents du Centre Amoricain d'Étude Structurale des Socles 24, 1–307.
Wagreich, M., 1995. Subduction tectonic erosion and Late Cretaceous subsidence along the northern Austroalpine margin (eastern Alps, Austria). Tectonophysics 242, 63–78.
Wagreich, M., 2001. A 400-km-long piggyback basin (Upper Aptian–Lower Cenomanian) in the Eastern Alps. Terra Nova 13 (6), 401–406. doi:10.1046/j.1365-3121.2001.00362.x.
Weber, J., Vrabec, M., Stopar, B., Pavlovčič-Prešeren, P., Dixon, T., 2006. The PIVO-2003 Experiment: A GPS study of Istria Peninsula and Adria microplate motion, and active tectonics in Slovenia. In: Pinter, N., Grenerczy, G., Weber, J., Stein, S., Medak, D. (Eds.), The Adria Microplate: GPS Geodesy, Tectonics and Hazards, NATO Science Series, Series IV: Earth and Environmental Sciences. Springer, pp. 305–320.
Weissert, H.J., Bernoulli, D., 1985. A transform margin in the Mesozoic Tethys: evidence from the Swiss Alps. Geologische Rundschau 74 (3), 665–679.
Westphal, M., Bazhenov, M., Lauer, J.P., Pechersky, D.M., Sibuet, J.-C., 1986. Paleomagnetic implications on the evolution of the Tethys belt from the Atlantic Ocean to the Pamirs since the Triassic. Tectonophysics 123, 37–82.
Wheeler, J., Reddy, S.M., Cliff, R.A., 2001. Journal of the Geological Society of London 158, 439–443.
Wiederkehr, M., Bousquet, R., Schmid, S.M., Berger, A., 2008. From subduction to collision: thermal overprint of HP/LT meta-sediments in the north-eastern Lepontine Dome (Swiss Alps) and consequences regarding the tectono-metamorphic evolution of the Alpine orogenic wedge. In: Froitzheim, N., Schmid, S.M. (Eds.), Orogenic Processes in the Alpine Collision Zone: Swiss Journal of Geosciences, 101, pp. S127–S155 (Supplement 1).
Wiederkehr, M., Sudo, M., Bousquet, R., Berger, A., Schmid, S.M., 2009. Alpine orogenic evolution from subduction to collisional thermal overprint: the 40Ar/39Ar age constraints from the Valaisan Ocean, Central Alps. Tectonics 28, 1–28. doi:10.1029/2009TC002496.
Winkler, W., 1988. Mid-to Early Late Cretaceous flysch and melange formations in the Western part of the Eastern Alps. Paleotectonic implications. Jahrbuch der Geologischen Bundesanstalt (Wien) 131 (2), 341–389.
Winkler, W., Bernoulli, D., 1986. Detrital high-pressure/low-temperature minerals in a late Turonian flysch sequence of the eastern Alps (western Austria): implications for early Alpine tectonics. Geology 14, 598–601.
Winkler, W., Bernoulli, D., Dal Piaz, G.V., Martin, S., 1997. 40Ar/39Ar laser probe dating of detrital white micas from Cretaceous sedimentary rocks of the Eastern Alps: evidence for Variscan high-pressure metamorphism and implications for Alpine orogeny: comment and reply. Geology 25 (8), 765–767.
Wortel, M.J.R., Spakman, W., 2000. Subduction and slab detachment in the Mediterranean–Carpathian region. Science 290, 1910–1917.
Wortmann, U.G., Weissert, H., Funk, H., Hauck, J., 2001. Alpine plate kinematics revisited: the Adria problem. Tectonics 20, 134–147.
Zeck, H.P., 1997. Mantle peridotites outlining the Gibraltar arc-centrifugal extensional allochthons derived from the earlier Alpine, westward subducted nappe pile. Tectonophysics 281, 195–207.
Ziegler, P.A., 1990. Geological Atlas of Western and Central Europe. 2. Edition, Shell Internationale Petroleum Maatschappij B.V., Den Haag. (239 pp.).
Zingg, A., Handy, M.R., Hunziker, J.C., Schmid, S.M., 1990. Tectonometamorphic history of the Ivrea Zone and its relation to the crustal evolution of the Southern Alps. Tectonophysics 182, 169–192.