Int J Earth Sci (Geol Rundsch) (2015) 104:1–26
DOI 10.1007/s00531-014-1060-3

REVIEW ARTICLE

Reconstructing the Alps–Carpathians–Dinarides as a key to understanding switches in subduction polarity, slab gaps and surface motion

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Received: 16 September 2013 / Accepted: 13 July 2014 / Published online: 21 September 2014

Abstract Palinspastic map reconstructions and plate motion studies reveal that switches in subduction polarity and the opening of slab gaps beneath the Alps and Dinarides were triggered by slab tearing and involved widespread intracrustal and crust–mantle decoupling during Adria–Europe collision. In particular, the switch from south-directed European subduction to north-directed "wrong-way" Adriatic subduction beneath the Eastern Alps was preconditioned by two slab-tearing events that were continuous in Cenozoic time: (1) late Eocene to early Oligocene rupturing of the oppositely dipping European and Adriatic slabs; these ruptures nucleated along a trench–trench transfer fault connecting the Alps and Dinarides; (2) Oligocene to Miocene steepening and tearing of the remaining European slab under the Eastern Alps and western Carpathians, while subduction of European lithosphere continued beneath the Western and Central Alps. Following the first event, post-late Eocene NW motion of the Adriatic Plate with respect to Europe opened a gap along the Alps–Dinarides transfer fault which was filled with upwelling asthenosphere. The resulting thermal erosion of the lithosphere led to the present slab gap beneath the northern Dinarides. This upwelling also weakened the upper plate of the easternmost part of the Alpine orogen and induced widespread crust–mantle decoupling, thus facilitating Pannonian extension and roll-back subduction of the Carpathian oceanic embayment. The second slab-tearing event triggered uplift and peneplainization in the Eastern Alps while opening a second slab gap, still present between the Eastern and Central Alps, that was partly filled by northward counterclockwise subduction of previously unsubducted Adriatic continental lithosphere. In Miocene time, Adriatic subduction thus jumped westward from the Dinarides into the heart of the Alpine orogen, where northward indentation and wedging of Adriatic crust led to rapid exhumation and orogen-parallel escape of decoupled Eastern Alpine crust toward the Pannonian Basin. The plate reconstructions presented here suggest that Miocene subduction and indentation of Adriatic lithosphere in the Eastern Alps were driven primarily by the northward push of the African Plate and possibly enhanced by neutral buoyancy of the slab itself, which included dense lower crust of the Adriatic continental margin.

Keywords Alps · Carpathians · Dinarides · Adria · Subduction polarity switch · Slab tearing · Slab gaps · Crust–mantle decoupling · Surface uplift

Introduction

Switches in subduction polarity—either stationary or migrating along convergent boundaries—exist in both subduction orogens (Taiwan, e.g., Tsai et al. 1977; Ustaszewski et al. 2012) and collisional mountain belts (Pamir-Hindukush, e.g., Burtman and Molnar 1993; Sippl et al. 2013), including the circum-Mediterranean Alpine mountain belt (e.g., Faccenna et al. 2004). The central part of this highly arcuate belt (Fig. 1) comprises the Alps proper, a classical

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Electronic supplementary material The online version of this article (doi:10.1007/s00531-014-1060-3) contains a link to supplementary material (Appendix, Parts A, B and C, including figures) which is available to authorized users.

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Fig. 1 Central segment of the Alpine–Mediterranean chain with orogenic fronts, basins and main localities mentioned in the text. The thrust vergence reflects the polarity of subduction, including polarity switches at the Alps–Apennines and Alps–Dinarides junctions discussed in this paper

collisional orogen which joins at either end with the Apennines, Carpathians and Dinarides (Fig. 2). Despite along-strike changes in thrust vergence, these mountain belts contain nearly continuous exposures of ophiolite and accretionary prisms that mark the remains of two oceanic basins, the Triassic–Jurassic Neotethys (Ricou 1994) and Jurassic–Early Cretaceous Alpine Tethys (e.g., Stampfli and Borel 2002; Schmid et al. 2008), which are overprinted by Late Cretaceous-to-Cenozoic calc-alkaline magmatism (Fig. 3).

The Alps themselves, long considered an archetypal orogen for cylindrism and uniform-sense subduction (Argand 1924), are actually characterized by two along-strike reversals in subduction polarity: one at their junction with the Apennines (Laubscher 1988; Molli 2008; Vignaroli et al. 2008) and another at their transition to the Dinarides (Laubscher 1971; Lippitsch et al. 2003; Kissling et al. 2006; Ustaszewski et al. 2008). These reversals coincide with striking differences in deformational style along the boundaries of the Adriatic Plate (here termed Adria) that formed during its Cenozoic convergence with Europe (Royden and Burchfiel 1989; Handy et al. 2010): In the Alps, the northern margin of Adria, together with the Adria-derived Austroalpine nappe pile, formed the upper plate to the Paleogene subduction of Alpine Tethys. The ensuing collision involved substantial accretion and exhumation of deeply subducted units from the downgoing European plate (Schmid et al. 1996, 2004). In the Apeninnes, however, Adria was the compliant lower plate during Neogene roll-back subduction (Malinverno and Ryan 1986; Royden 1993) and collision (Moretti and Royden 1988; Faccenna et al. 2004). Likewise in the Dinarides, Adria was the lower plate during the entire Cretaceous to Cenozoic orogenic evolution (Schmid et al. 2008). These opposing subduction polarities persist today; the rigid northern promontory of Adria (the so-called Adriatic indenter) is still rotating counterclockwise and indenting the Eastern Alps and Dinarides (e.g., Nocquet and Calais 2004; Vrabec and Fodor 2006 and references therein), while the southern part is subducting beneath the advancing Hellenides (Grenerczy et al. 2005; Burchfiel et al. 2008; Bennett et al. 2008).

Debate on changing subduction polarity in the Alps has been galvanized in the past decade by teleseismic tomographic images of two positive compressive-wave velocity ($+V_{\mathrm{p}}$) slab anomalies with contrasting orientations beneath the Alps (Fig. 4a–c): one beneath the Central and Western Alps that dips to the southeast to a depth of about 200 km and is consistent with the classical view of south- to southeast-directed subduction of European lithosphere (e.g., Schmid et al. 1996), and another beneath the Eastern Alps that is oriented the wrong-way for European subduction; instead, it dips northward to a depth of at least 210 km (Lippitsch et al. 2003) or more (Dando et al. 2011; Mitterbauer et al. 2011). Controversy surrounds the proposed northward dip of the latter anomaly, partly due to its incompatibility with conventional notions of southward European subduction beneath the Alps, and partly because of the ambiguity of tomographic images in this region (Mitterbauer et al. 2011). Nevertheless, the generally northward dip of the $+V_{\mathrm{p}}$ Eastern Alps anomaly in Lippitsch et al. (2003) is regarded as a robust feature because their model is unique in incorporating a high-resolution 3D model of crustal velocities specific to the Alps. An important feature of all tomographic models so far is a narrow but distinct gap between the two $+V_{\mathrm{p}}$ anomalies at the junction of the Western-Central and Eastern Alps as marked in Fig. 4a. We will return to this feature below, but emphasize that the existence of this gap is difficult to reconcile with the classical notion of a single, continuous slab beneath the entire length of the Alps.

Taken at face value, the tomographic model of Lippitsch et al. (2003) indicates a fragment of Adriatic lithosphere entrained beneath the Eastern Alps (Schmid et al. 2004; Horváth et al. 2006; Kissling et al. 2006). This is consistent with the southwestward vergence of thrusts and folds in the Dinarides, as well as with images of a northward-dipping slab along the still-active Hellenic arc-trench system (Fig. 4d, Bijwaard and Spakman 2000; Piromallo and Morelli 2003; Spakman and Wortel 2004; Zhu et al. 2012). Alternatively, Mitterbauer et al. (2011) proposed that the $+V_{\mathrm{p}}$ anomaly beneath the Eastern Alps is vertical to steeply northeast-dipping and represents European lithosphere that originally subducted to the south, but was subsequently steepened and overturned.

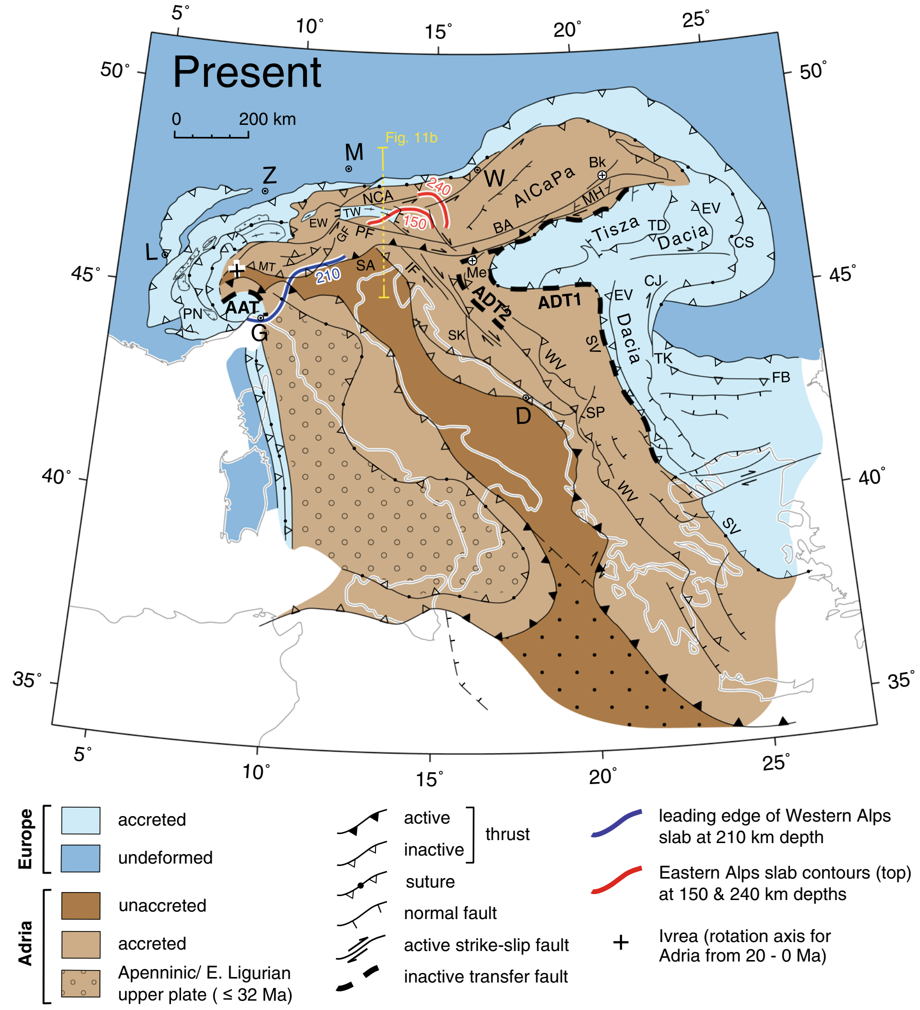


Fig. 2 Tectonic map of the Alps, Apennines, Carpathians and Dinarides showing main faults, tectonic units, and surface traces of slabs beneath the Alps. *Red* and *blue lines* indicate depth contours (km) of positive P-wave velocity ($+V_p$) anomalies projected to the surface, respectively, for the Eastern Alps slab and the leading edge of European slab. Localities: *D* Dubrovnik, *G* Genoa, *L* Lyon, *M* Munich, *W* Wien (Vienna), *Z* Zürich. Tectonic units and structures: AAT—Alps–Apennines Transfer Fault, ADT1 and ADT2—Alps–Dinarides Transfer Faults, AlCaPa—Alps–Carpathians–Pannonian unit, CJ—Cerna Jiu Fault, CS—Ceahlau–Severin Suture, EN—Engadine Window, EV—East Vardar ophiolite front, EW—Engadine Window, FB—Forebalkan Front, GF—Giudicarie Fault and Thrust Belt, IF—Idrija Fault, PN—Penninic Front, MH—Mid-Hungarian Fault Zone, MT—Milan Thrust Belt, NCA—Northern Calcareous Alps, PF—Periadriatic Fault System, including Balaton Fault (BA), SA—Southern Alps Front, SK—Split-Karlovac Fault, SV—Sava Suture Zone, SP—Scutari-Peç Fault, TD—Tisza–Dacia boundary fault, TK—Timok Fault, TW—Tauern Window, WV—West Vardar ophiolite front. *Circles with crosses* represent the Bükk Mtns. Unit (Bk) and Medvednica Unit (Me) used as structural markers (see text). *Black stipples* represent oceanic lithosphere. Main faults taken from Horváth et al. (2006) (Carpathians, Pannonian Basin), Molli (2008) and Molli et al. (2010) (northern Apennines), Schmid et al. (2004, 2008) (Alps, Carpathians, Pannonian Basin, Dinarides), Burchfiel et al. (2008) and Burchfiel and Nakov (2014) (Forebalkan Orogen). Slab contours from Lippitsch et al. (2003)

Whatever the plate tectonic affinity of this anomaly, explanations of how it got there must account for another unusual feature, a large low-velocity ($-V_p$) anomaly beneath the northern Dinarides that separates the aforementioned slab anomaly in the Eastern Alps from the slab anomaly beneath the Hellenides (Fig. 4d). A slab gap beneath the Dinarides is surprising given the significant amount of shortening implicit in Late Cretaceous to Mio-Pliocene thrusting there (Schmid et al. 2008; Ustaszewski et al. 2008). Contrasting thrust vergences and subduction polarities in the Alps and Dinarides have existed since at least Late Cretaceous time (Ustaszewski et al. 2008), but the location of this polarity switch is unknown and, indeed, may have moved since the onset of subduction.

In this paper, we test the idea of late collisional, north-directed “wrong-way” subduction of continental lithosphere beneath the Eastern Alps. To do this, we construct paleotectonic maps for the Alpine chain that reveal the locations of slabs and slab gaps at crucial time intervals during Adria–Europe convergence (sections "Reconstructing Adria–Europe convergence and past slab geometries" and "Plate and crustal motions in the central Mediterranean area since 84 Ma"). We demonstrate that the slab beneath the Eastern Alps subducted in Miocene time and is derived primarily from Adriatic continental margin in the Eastern and Southern Alps (section "Origin of the slab anomaly beneath the Eastern Alps"). This subduction decoupled the mantle from the overlying orogenic crust which underwent coeval folding, extensional exhumation and orogen-parallel escape toward the Pannonian Basin (section "Kinematics of Adriatic subduction and crustal indentation in the Alps"). We propose that wrong-way subduction of continental lithosphere was conditioned by late Eocene–Oligocene rupturing of the European and Adriatic slabs in the vicinity of a transfer fault connecting the opposite Alpine and Dinaric subductions. Finally, we discuss the factors favouring northward subduction of Adriatic continental lithosphere in Miocene to recent times (section "Forces driving northward subduction of Adriatic continental lithosphere in the Alps") and show how decoupling of crust, lithospheric mantle and asthenosphere were crucial for the emplacement of slabs in the Alpine system (section "Slab dynamics, mantle flow and decoupling in the Alps–Carpathian–Dinarides belt").

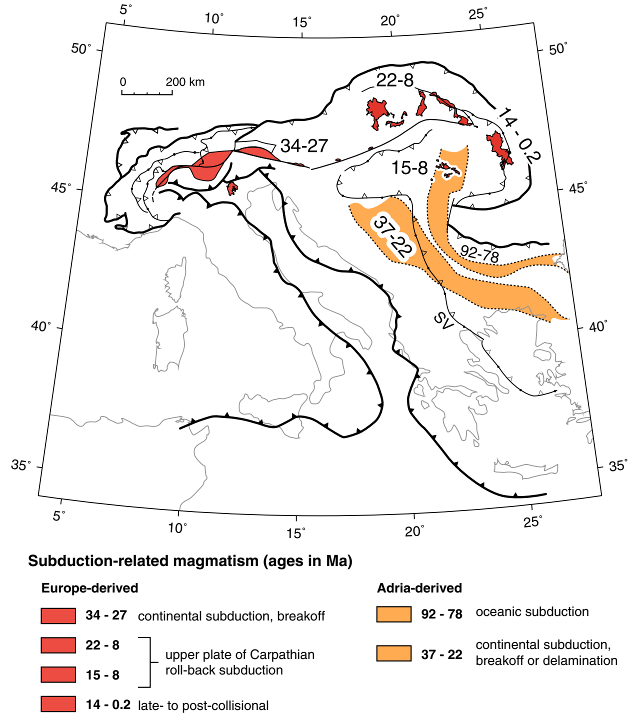
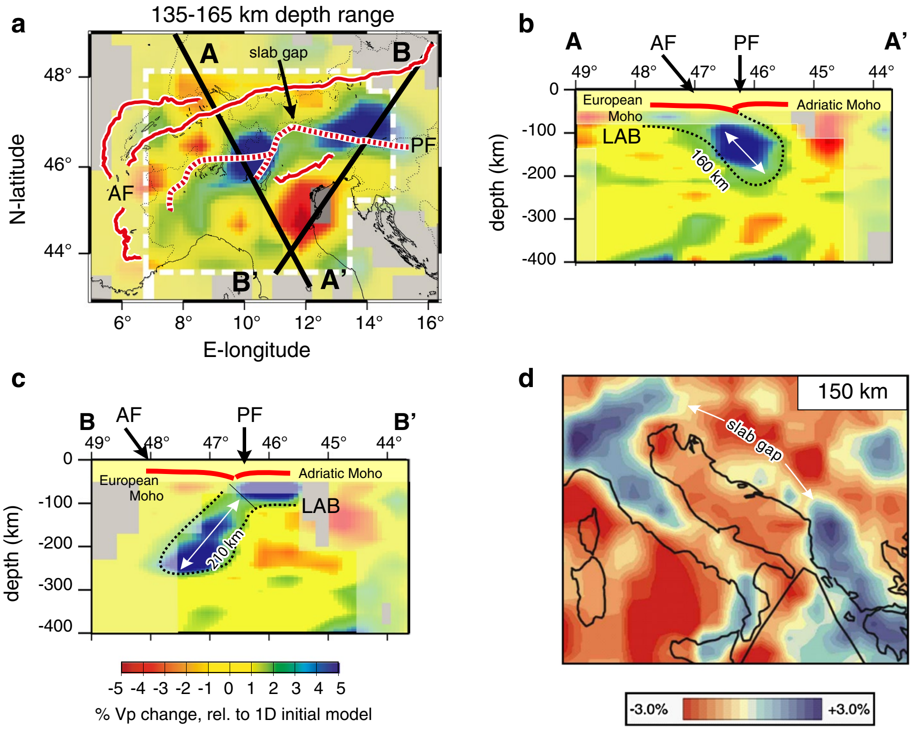


Fig. 3 Magmatic domains in Alps, Carpathians and Dinarides with ages in millions of years (Ma) compiled from Harangi et al. (2006), their Fig. 5, Pécskay et al. (2006), their Fig. 4, Seghedi and Downes (2011), their Fig. 3 (Carpathian–Pannonian area), Rosenberg 2004 (Alps) and Schefer et al. (2011) (Dinarides). Magmatic domains in the Apennines, Tyrrhenian Sea and Sardinia are not shown. SV—Sava Suture Zone. Open and closed triangles indicate inactive and active orogenic fronts, respectively

Fig. 4 **a** Tomographic map of the 135–165 km depth range showing slab anomalies and slab gap beneath the Alps; **b** profile *A–A′* and **c** profile *B–B′* showing inclined $+V_p$ slab anomalies with opposite polarities beneath the Central and Eastern Alps (modified from Lippitsch et al. 2003); **d** Tomographic map at 150 km depth showing slab gap beneath the Dinarides (modified from Bijwaard and Spakman 2000). *AF* Alpine Front, *PF* Periadriatic Fault, *LAB* lithosphere–asthenosphere boundary



Reconstructing Adria–Europe convergence and past slab geometries

Paleotectonic maps of the Alpine chain

The plate reconstructions and cross sections in Figs. 5, 6, 7, 8, 9, 10 and 11 show the main structures at key times in the evolution of the Alpine chain. They also include the restored locations of the slab anomaly that presently dips to the north beneath the Eastern Alps. In all four paleotectonic maps (Figs. 5, 6, 8, 10), the leading edge of this slab was restored to the horizontal attitude it had prior to subduction (section "Restoring the Alpine slabs", also Appendix, Fig. B2, bottom).

In this section, we summarize the complex reconstruction procedure and highlight points that pertain to the emplacement of the slabs, particularly of the slab imaged below the Eastern Alps today. The many steps and sources used to reconstruct the tectonics and slab locations are explained in parts A and B of the Appendix, which is available in the online repository or from the first author. To aid the reader, reference is made in parentheses to pertinent sections and figures of the Appendix where details are explained more thoroughly.

The motions of the Adriatic Plate and Alpine thrust fronts with respect to the European Plate are based on estimates of shortening and extension from tectonically balanced cross sections and 2-D map restorations (Figs. A1a, b). These estimates were used to retrodeform the thrust fronts successively from external to internal parts of the Alps (Figs. A2, A3); the motions of the hinterland pin lines on these cross sections were applied as stepwise retrotranslations of a point at the city of Ivrea on the stable (unaccreted) part of the Adria Plate with respect to the stable European foreland (Figs. A4 to A11 back to 84 Ma; see Appendix, part A). Ivrea in northwestern Italy is a convenient reference point on Adria due to its proximity both to a relatively undeformed, distal part of the Adriatic margin to Alpine Tethys (Handy and Zingg 1991) and to the pole of post-20 Ma counterclockwise rotation of Adria. Shortening of accreted Adriatic crust (light brown units in Figs. 5, 6) was restored similarly, but involved retrotranslations of stable Adria with respect to the Periadriatic Fault. This fault delimits the southernmost units in the Alps affected by penetrative Cenozoic deformation (Schmid et al. 1989).

Adria's motion relative to Europe is represented in all maps by a vector connecting past locations of Ivrea. We emphasize that this vector is only an approximation of the true motion of Adria due to aspects of the restoration method that have opposite effects on the overall displacement path: On the one hand, the shortening values from individual thrusts are minimum displacements because thrust fronts and their hangingwall cutoff lines have been eroded, and also because out-of-sequence thrusting in the Alps may have involved tectonic erosion of accreted material from the orogenic wedge (A2). On the other hand, Adria's Neogene motion is probably overestimated somewhat due to space problems that arise within the Western Alpine arc when retrodeforming thrusts that were active during and after oroclinal bending (A3.7). Despite these methodological limitations, the amount of Adria–Europe convergence implied by the motion path for Adria in Figs. 5 and 6 is broadly consistent with the lengths of slab anomalies in teleseismic images, as discussed below in section ""Wrong-way" subduction in the Eastern Alps, roll-back subduction in the Carpathians" (see also A3.7 and A4.1.3). This vector is fairly straight from 84 to the present compared to the previously published path for an independent Adriatic Plate in Handy et al. (2010), which involved a pronounced change to more westward motion beginning at 35 Ma. The absence of this change here reflects a combination of more Paleogene N–S shortening in the Alps (mostly in the Helvetic Nappes) and less E–W motion along the Periadriatic Fault, as discussed in the Appendix, sections A4.1 and A4.5. Preliminary plate motion studies suggest that the straighter post-35 Ma motion path of Adria obtained here is consistent with recently constrained motions for Iberia and Africa over the same time span (E. Le Breton, personal communication).

Restoring the Alpine slabs

Restoring the leading edge of the slab beneath the Eastern Alps (red lines in Fig. 2) starts with two basic steps: (1) horizontalization of the slab edge about a horizontal axis oriented parallel to the average trend of the 4 % anomaly defining the slab surface in the tomographic depth slices of Lippitsch et al. (2003), as discussed in section B of the Appendix (see Figs. B1, B2 and B3). The trend of this rotation axis is parallel to the Periadriatic Fault which forms the southern boundary of the Eastern Alps (Fig. B3); (2) backrotation of the slab edge about a vertical axis at Ivrea corresponding to the aforementioned Miocene-to-Recent rotational pole for the counterclockwise rotation of the Adria (Fig. B4). This pole is defined by the eastward increase in post-Oligocene shortening of the Southern Alps (Appendix section A3.5 and Fig. A8).

Horizontalizing the slab requires different amounts of backrotation about the flat rotational axis due to along-strike variations in the dip of the slab (Fig. A3). This varied backrotation angle reflects the highly irregular geometry of the slab as outlined in tomographic depth slices by the changing shape of the slab image with depth; at 150 km depth the image is oblong, with an arcuate upper surface that trends oblique to the Periadriatic Fault System (Fig. B1a), whereas from 210 km down to the slab tip at 240 km, the image becomes round and migrates to the northeast (Fig. B1b, c). Therefore, the $+V_p$ anomaly beneath the Eastern Alps does not have a truly slab-like geometry and must have undergone significant deformation during subduction, a point to which we return below when considering the kinematics of slab emplacement. Further retrotranslations of the horizontalized slab back to 35, 67 and 84 Ma treat the slab as lithosphere that was attached to the Adriatic plate (Appendix sections B2.3 and B2.4, Figs. B5, B6, B7).

The leading edge of the European slab below the Western and Central Alps (blue contour line in Fig. 2) was horizontalized in the same way (Fig. B3) except that no rotations about a vertical axis were necessary in light of clear evidence from thrust and fold vergences in the Alps (Handy et al. 2010, their Fig. 5) that subduction of this slab was to the SE, i.e., parallel to the dip of the $+V_p$ anomaly. We note that the length of the European slab in the south to southeasterly direction of subduction yields an independent measure of minimum shortening in the Central Alps since slab break off in late Eocene time (von Blanckenburg and Davies 1995). The slab length measured in this direction was assumed in our map reconstructions in Figs. 5 and 6 to be the distance between the edge of the European margin (where the slab ruptured at c. 35–40 Ma) and the present Alpine thrust front at the base of the Subalpine Molasse, as discussed in the next section.

Plate and crustal motions in the central Mediterranean area since 84 Ma

Figures 5 and 6 show changes in the motion and shape of the Adriatic Plate during subductions of Alpine Tethys in the Alps and Neotethys in the Dinarides. To aid our discussions, we include a series of cross sections in Fig. 7 across the Eastern Alps and the eastern part of the Tauern Window. They are oriented parallel to the motion vector of the Adriatic plate with respect to Europe as indicated by the successive positions of the crosses marking the location of Ivrea in Fig. 5.

Subduction of Neotethys and Alpine Tethys, Alps–Dinarides transfer faulting

Subduction in the Alps

The 84 Ma map (Fig. 5) and its corresponding cross section (Fig. 7a) depict the initial northwestward convergence of Adria with the European margin. Coniacian to Santonian flysch in the footwall of the Austroalpine nappes yield a conservative (youngest) age for the onset of Alpine Tethys subduction (Handy et al. 2010 and refs. therein). However, subduction may have begun some 5–7 Ma earlier if one considers the local occurrence of Turonian orogenic flysch along central parts of the active margin (Arosa and Walsertal Zones in the eastern Central Alps, Oberhauser 1983) and the time to subduction of 84 Ma eclogites along the western part of this same margin (Corsica, Lahondère and Guerrot 1997). By 84 Ma, accretion of the Austroalpine thrust sheets to the leading edge of the Adriatic plate as part of the Cretaceous age, Eo-Alpine orogen was complete. Eo-Alpine accretion began at about 130 Ma with detachment of the far-traveled Mesozoic cover nappes from the Adriatic (Hallstatt) margin of Neotethys presently exposed in the Northern Calcareous Alps (Fig. 2, e.g., Faupl and Wagreich 2000; Mandl 2000). Eo-Alpine events are not considered further here, as they have little obvious bearing on the changes in subduction polarity in the Alps and Dinarides.

Subduction in the Dinarides, initial transfer faulting (ADT1)

Subduction of the Adriatic Plate beneath the European Plate occurred since at least 92 Ma based on the age range of calc-alkaline magmatism in internal parts of the Dinarides (92–78 Ma "banatite" magmatic suite in Fig. 3), although older calc-alkaline magmatites of up to 110 Ma indicate that subduction may have begun even earlier (e.g., Pamić et al. 2000). Subduction at 84 Ma in the Dinarides (Fig. 5) affected primarily the Sava oceanic domain (Pamić 2002), which is interpreted as a remnant basin of Neotethys (Meliata–Maliac–Vardar ocean of Schmid et al. 2008) that remained open after the Late Jurassic obduction. The obduction front is the thrust marked WV in Fig. 5. The Sava Basin underwent minor spreading or ocean island volcanism in the downgoing Adriatic plate (Ustaszewski et al. 2009). In Fig. 5, this narrow basin is depicted with paleo-transform offsets oriented at high angles to the east–west trend of the rifted margin, in keeping with the idea that this oceanic basin opened in the upper plate of the Dinaric orogen advancing to the south to southwest (Schmid et al. 2008).

The opposing polarity of Alpine and Dinaric subductions in Late Cretaceous time calls for a major transfer fault, here named the Alps–Dinarides Transfer Fault (ADT1), which in Figs. 5 and 6 connected the Alpine thrust front with the Dinaric front located along the future Sava Suture Zone. For convenience, the ADT1 is drawn parallel to the Adria–Europe convergence vector and subparallel to the trend of the rifted Adriatic margin of the Sava Basin. The original orientation of the ADT1 is poorly constrained, especially in the vicinity of the later ADT2 beneath the Pannonian Basin where Miocene rifting and subsequent block rotations, strike-slip faulting and sedimentation severely modified older structures (section "Change from Alps–Dinarides transfer faulting to Adriatic indentation and Carpathian roll-back subduction").

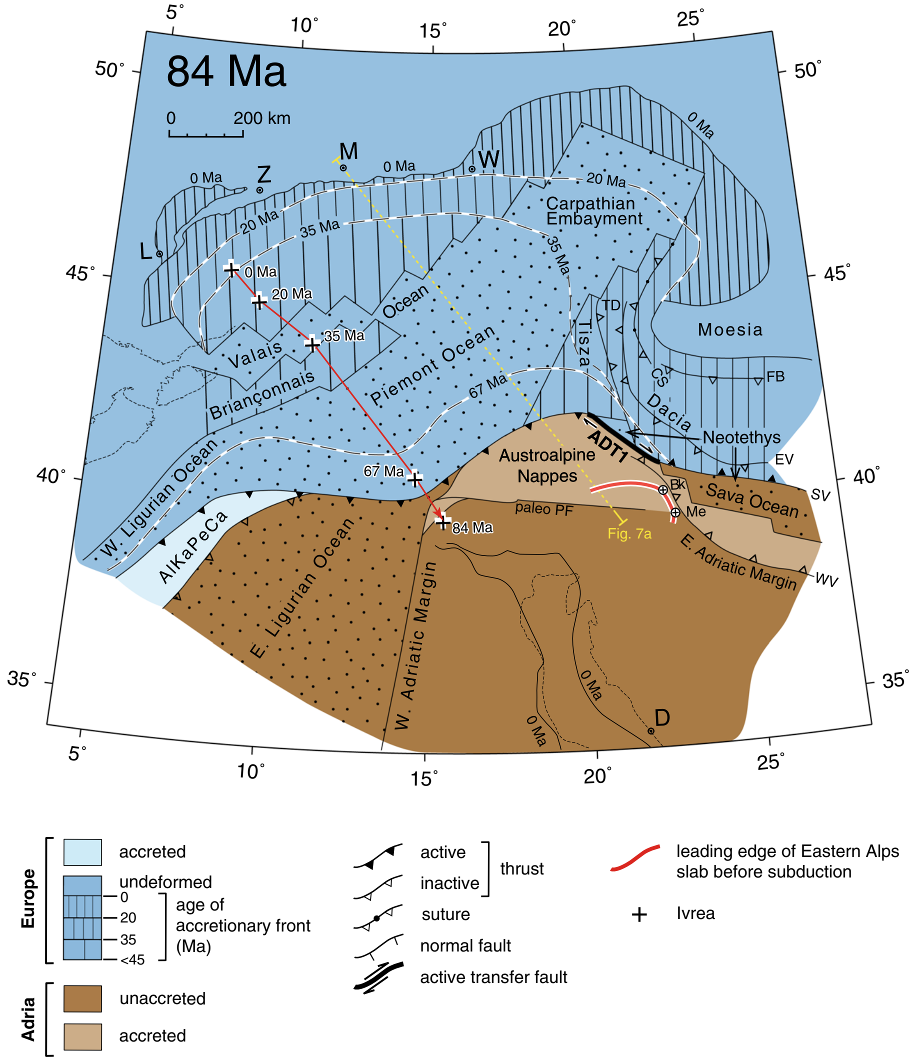


Fig. 5 Paleotectonic map for 84 Ma: Onset of Alpine Tethys subduction, end of Eo-Alpine orogenesis. Note the length of Alpine active margin reaching from the Western Ligurian Sea to the ADT1 in the east. ADT1—Late Cretaceous to mid-Eocene Alps–Dinarides Transfer Fault, AlKaPeCa—Alboran–Kabylia–Peloritani–Calabria continental fragment, CS—Ceahlau-Severin Suture, EV—East Vardar ophiolite front, FB—Forebalkan Front, paleo-PF—pre-late Eocene precursor of the Periadriatic Fault, WV—West Vardar ophiolite front. *Circles with crosses* represent the Bükk Mtns (Bk) and Medvednica (Me) Units used as markers. *Black stipples* represent oceanic lithosphere. *Black crosses* connected by *red line* show successive locations of Ivrea that define the motion path of the Adriatic Plate with respect to Europe. *Dashed black* and *white lines* indicate future locations of the Alpine orogenic front at 67, 35 and 20 Ma. *Red line* indicates horizontalized leading edge of Eastern Alps slab

Suturing of Neotethys

At 67 Ma (Fig. 6), suturing of the Sava back-arc basin marked the onset of Dinaric collision. The age of suturing is constrained by deformed Maastrichtian (70.6–65.5 Ma) siliciclastic sediments of the Sava Suture Zone that were deposited in an underfilled orogenic foredeep (Ustaszewski et al. 2010) and contain components derived from both European units of the hangingwall (Tisza, Dacia, Fig. 6) and internal Adriatic units of the footwall. Detrital minerals in these sediments experienced slow cooling from peak Barrovian burial metamorphism at about 65 Ma, placing a younger limit on the age of suturing (Ustaszewski et al. 2010 and refs. therein).

The European margin south and east of the Carpathian oceanic embayment (Figs. 5, 6) contains several thrust fronts of Cretaceous age (marked TD, EV and CS) that are depicted as originally oriented subparallel to the southern European margin of the embayment. This trend is speculative and reflects the notion that the sutures localized rifting and spreading of the embayment in late Jurassic–Early Cretaceous time. However, their original trend is unknown, as they were reactivated and reoriented during late Eocene to Miocene oroclinal bending around the Moesian promontory of Europe (Fig. 8, Fügenschuh and Schmid 2005, their Fig. 9).

Paleogene transfer faulting (ADT2)

In Paleogene time, transfer faulting at the Alps–Dinarides join shifted to the west to a new site, the ADT2, with respect to the deactivated ADT1 along the northern part of the Sava Suture Zone (Fig. 8). This suture zone ceased to be a transfer fault no later than about 40 Ma as constrained by apatite fission-track ages which date accelerated cooling of this zone in the hangingwall of the externally propagating Dinaric thrust front (Ustaszewski et al. 2010). The Sava Suture Zone became the site of W- to SW-directed post-Paleocene thrusting, which was probably coeval with

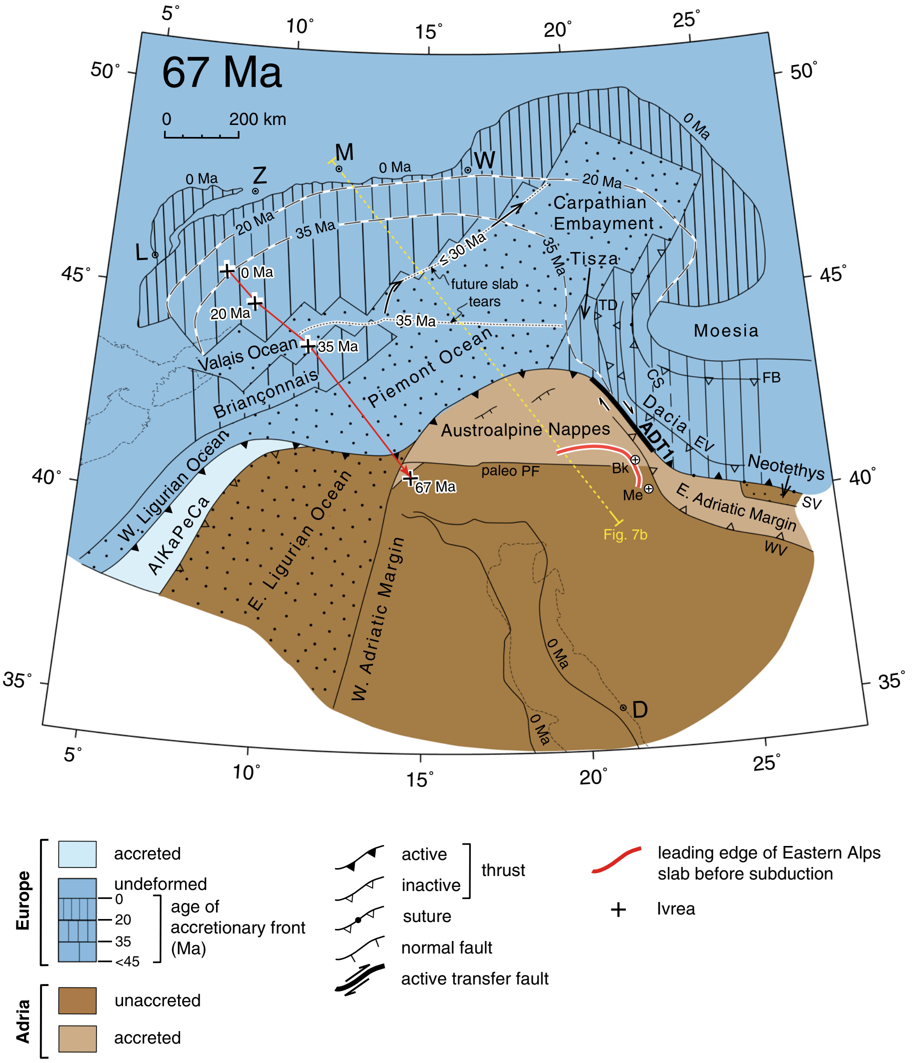


Fig. 6 Paleotectonic map for 67 Ma: Neotethys suturing, Dinaric collision. ADT1—Late Cretaceous to mid-Eocene Alps–Dinarides Transfer Fault, AlKaPeCa—Alboran–Kabylia–Peloritani–Calabria continental fragment, CS—Ceahlau–Severin Suture, EV—East Vardar ophiolite front, FB—Forebalkan Front, paleo-PF—pre-late Eocene precursor of the Periadriatic Fault, TD—Tisza–Dacia boundary fault, WV—West Vardar ophiolite front. *Circles with crosses* represent the Bükk Mtns (Bk) and Medvednica (Me) Units. *Black stipples* represent oceanic lithosphere. *Black crosses* connected by *red line* show successive locations of Ivrea that define the motion path of the Adriatic Plate with respect to Europe. *Dashed black* and *white lines* indicate future locations of the Alpine orogenic front at 35 and 20 Ma. *Red line* indicates horizontalized edge of slab beneath Eastern Alps

the mid-Eocene to Oligocene main phase of thrusting in the External Dinarides (Tomljenović et al. 2008, see A4.4).

We propose that the ADT2 linked the Alpine orogenic front with its foredeep (containing the Rheno-Danubian and Magura flysch, respectively, in the Eastern Alps and western Carpathians) with one or more late Eocene–early Oligocene thrusts in the External Dinarides (e.g., Picha 2002; Tari 2002; Carminati et al. 2012) located in the footwall of the West Vardar ophiolite front, as shown in Fig. 8. Possible candidates include the basal thrusts of the East Bosnian-Durmitor, Pre-Karst or High-Karst units (Table A1 in the Appendix). In the northern Dinarides, the ADT2 was affected by Miocene clockwise rotation (section "Change from Alps–Dinarides transfer faulting to Adriatic indentation and Carpathian roll-back subduction") and follows Paleogene thrusts north of and around the Medvednica Mountains Unit located north of Zagreb (marked Me in Figs. 2, 8). The ADT2 formed the eastern boundary of the future Eastern Alps slab, as discussed below in the section "Origin of the slab anomaly beneath the Eastern Alps." The originally northernmost part of the ADT2 is overprinted by the Miocene Mid-Hungarian Fault Zone beneath the Pannonian Basin with its thick cover of Mio-Pliocene sediments, as proposed by Schmid et al. (2008).

Alpine collision, rupturing of European and Adriatic slabs, magmatism

Paleogene shortening in the Alps

The entry of the European margin into the Alpine trench (Fig. 7c) is recorded by Priabonian flysch in distal Ultrahelvetic units and by late Eocene, high-pressure subduction metamorphism in Subpenninic internal basement nappes presently exposed in the core of the Alps (Berger and Bousquet 2008 and refs. therein). In the Western Alps, the northward component of Adria–Europe convergence was accommodated by north-vergent thrusting and folding in the pro-wedge (Helvetic domain, Kempf and Pfiffner 2004) and

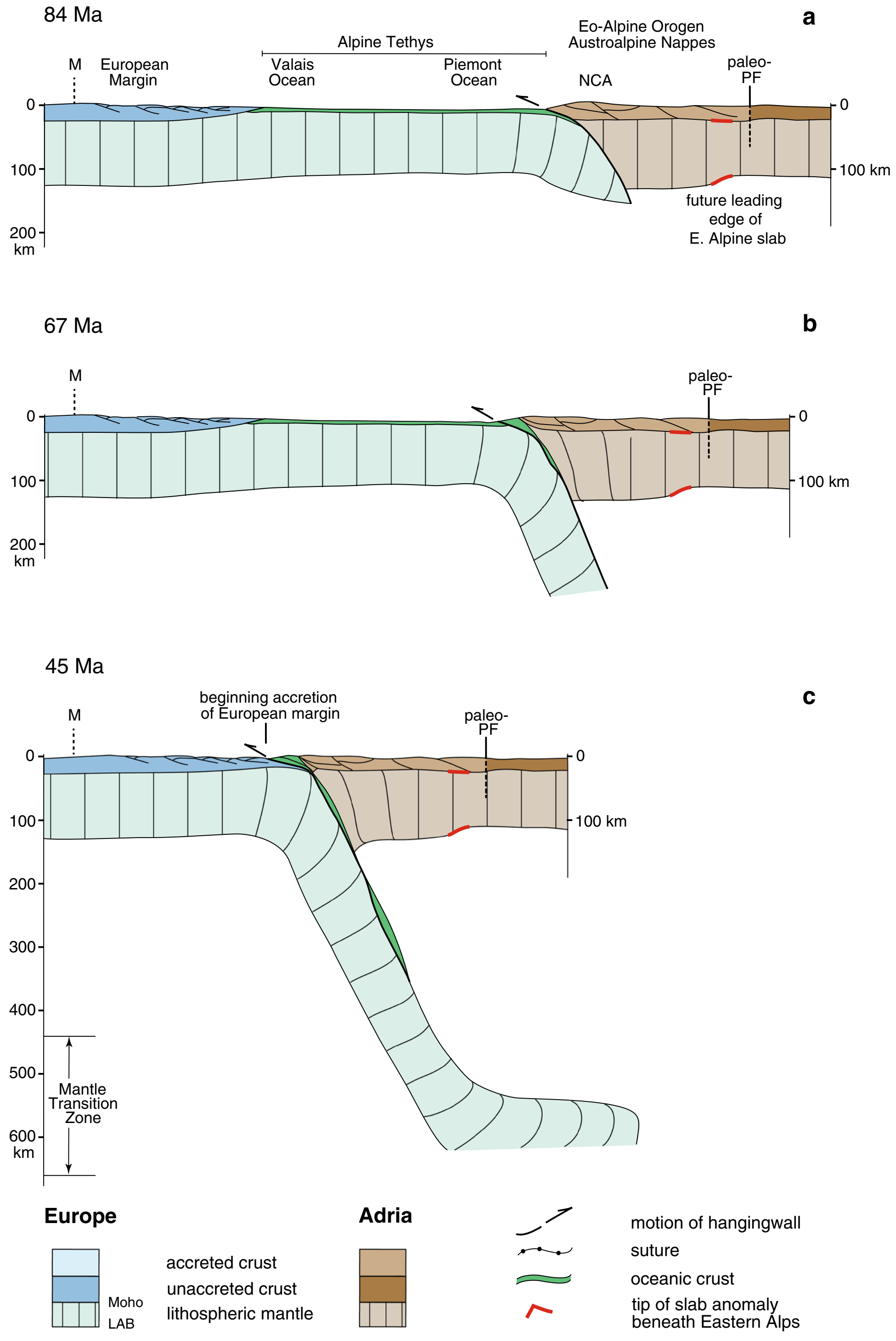


Fig. 7 Cross sections across the eastern part of the Alpine orogen in late Cretaceous time: **a** 84 Ma: Initial subduction of Alpine Tethys; **b** 67 Ma: continued subduction of Alpine Tethys, accretion of oceanic crust; **c** 45 Ma: onset of collision. Trace of cross sections **a**, **b** shown in Figs. 5 and 6

by southeast-vergent backfolding and thrusting in the retrowedge, deforming the basement nappes just north of the western (Tonale–Canavese) segment of the Periadriatic Fault System ("backfolding" in Fig. 8, Keller et al. 2005, their Fig. 14).

In the Eastern Alps, this convergence was accommodated primarily by north-directed thrusting of the Late Cretaceous Austroalpine nappe pile over the Penninic units, as seen at the transition of Western and Eastern Alps in eastern Switzerland (Milnes 1978), in the Tauern Window area (e.g., Pestal et al. 2009), and the Northern Calcareous Alps (Eisbacher et al. 1990; Linzer et al. 2002). In the eastern part of the Southern Alps, i.e., east of the Giudicarie

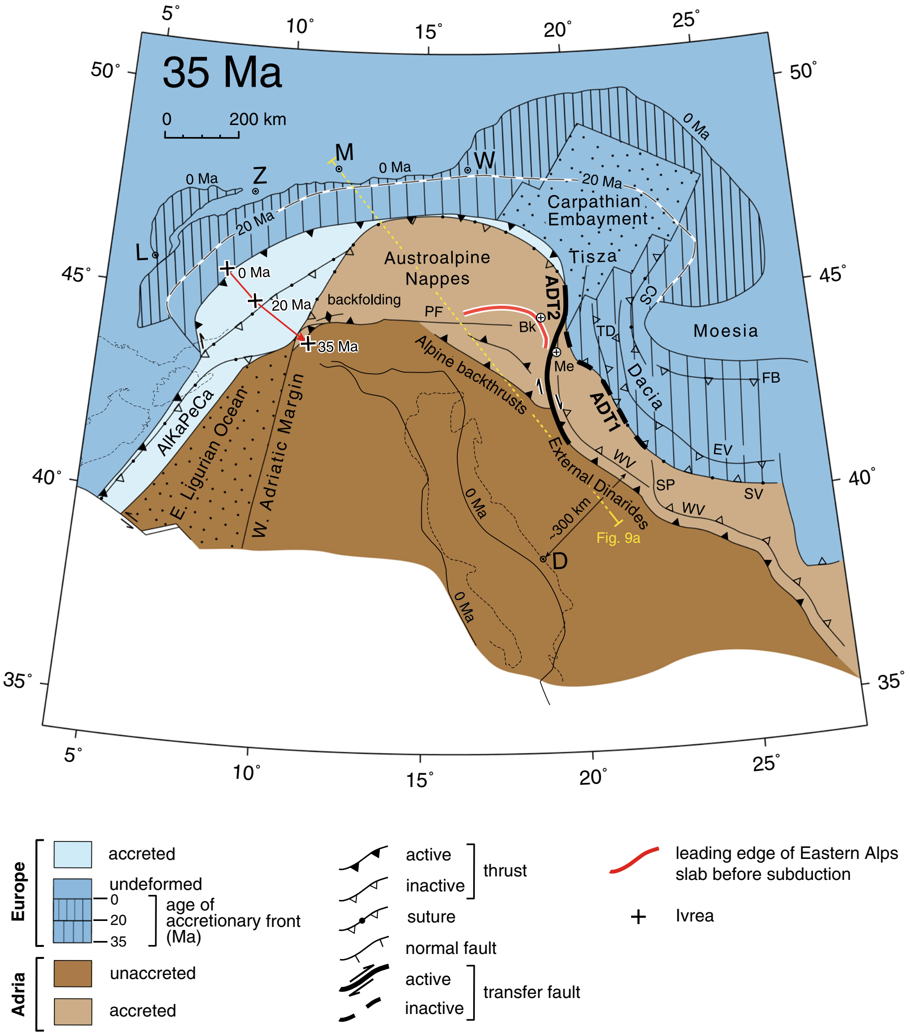


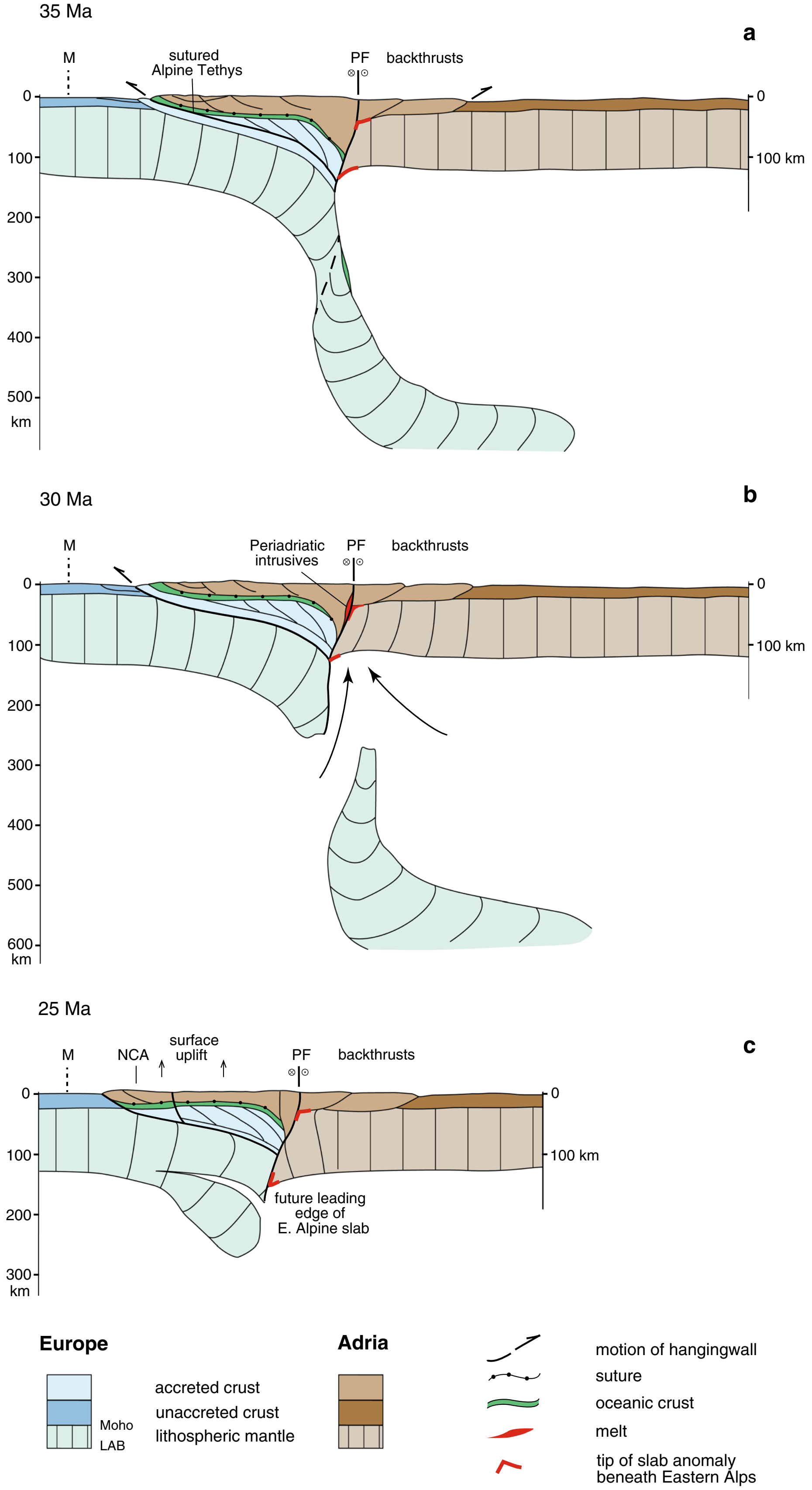
Fig. 8 Paleotectonic map for 35 Ma: Collision in Alps and Dinarides connected by the mid-Eocene to early Miocene Alps–Dinarides Transfer Fault (ADT2). Note that the estimated 300 km of post-late Eocene shortening in the Dinarides is only valid for 20° of post-20 Ma counterclockwise rotation of Adria with respect to Europe; smaller rotations yield correspondingly less shortening. ADT1—deactivated Late Cretaceous to mid-Eocene Alps–Dinarides Transfer Fault, AlKaPeCa—Alboran–Kabylia–Peloritani–Calabria continental fragment, CS—Ceahlau-Severin Suture, EV—East Vardar ophiolite front, FB—Forebalkan Front, PF—Periadriatic Fault, TD—Tisza–Dacia boundary fault, WV—West Vardar ophiolite front. *Circles with crosses* represent the Bükk Mtns (Bk) and Medvednica (Me) Units. *Black stipples* represent oceanic lithosphere. *Black crosses* connected by *red line* show successive locations of Ivrea that define the motion path of the Adriatic Plate with respect to Europe. *Dashed black* and *white line* indicates future location of the Alpine orogenic front at 20 Ma. *Red line* indicates horizontalized leading edge of the Eastern Alps slab

Fault (GF) (Fig. 2) in the Dolomites, Carnian and Julian Alps, SSW-vergent Paleocene to Eocene folds and thrusts ("Dinaric" phase of Cousin 1981; Doglioni 1987) are interpreted here as backthrusts of the Alpine orogen (Figs. 8, 9a, b) rather than direct continuations of the External Dinaric thrusts. Although this backthrusting was contemporaneous with southwest-directed thrusting in the External Dinarides, we propose that the backthrusts were decoupled from the latter along the ADT2 (Fig. 8). The Dinaric-trending backthrusts in the Southern Alps are overprinted by Tortonian to Pliocene, south–southeast-vergent folds and thrusts (Fig. 10, e.g., Doglioni 1987; Schönborn 1999; Castellarin and Cantelli 2000), some of which remain active to the present day (Benedetti et al. 2000; Merlini et al. 2002).

Periadriatic Faulting and initial slab tearing in the Alps and Dinarides

At 35 Ma, dextral motion on the Periadriatic Fault System began to accommodate the westward component of Adriatic motion with respect to Europe (Fig. 8). In our reconstruction, pre-20 Ma Cenozoic strike-slip motion on this part of

Fig. 9 Cross sections across the eastern part of the Alpine orogen in Paleogene time: **a** 35 Ma: Alpine orogenesis and incipient rupturing of European slab; **b** 30 Ma: first break off of European slab and Periadriatic magmatism; **c** 25 Ma second break off or delamination of European slab and surface uplift in the Eastern Alps (see section "Separation of the western and eastern Adriatic indenters"). Note that the slab resulted from continued Adria–Europe post-collisional convergence from 35 to 25 Ma. Trace of cross section for **a** shown in Fig. 8



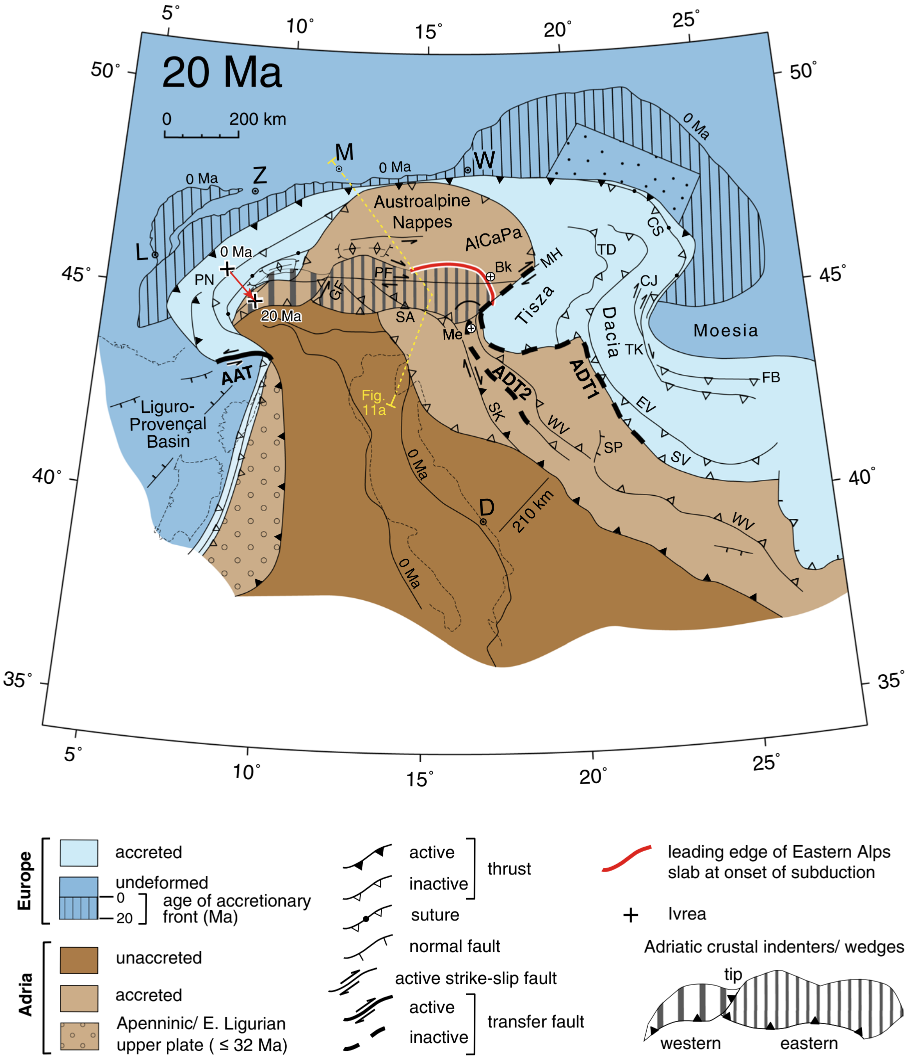


Fig. 10 Paleotectonic map of the Apennines–Alps–Carpathians–Dinarides belt for 20 Ma: Adriatic indentation of the Eastern Alps, lateral escape of AlCaPa unit into Pannonian Basin, Carpathian roll-back subduction, arcuation of Western Alps. In the Dinarides, northward motion of Adria was accommodated by Dinaric thrust faults delimited to the west by the Split-Karlovac Fault (SK) connecting the External Dinaric thrust front with the Southern Alps Front (SA). Thick red line shows position of the Eastern Alps slab at the onset of northward subduction. Curved black arrow indicates Mio-Pliocene clockwise rotation of the southern Alps and northern Dinarides. AAT—Alps–Apennines Transfer Fault, ADT1 and ADT 2—deactivated Alps–Dinarides Transfer Fault, CJ—Cerna–Jiu Fault, FB—Forebalkan Front, GF—Giudicarie Fault, MH—Mid-Hungarian Fault Zone, MT—Milan Thrust Belt, PF—Periadriatic Fault System, PN—Penninic Front, SA—Southern Alps Front, SK—Split-Karlovac Fault, SP—Scutari-Peç Fault, TD—Tisza–Dacia boundary fault, TK—Timok Fault, WV—West Vardar ophiolite front. Black crosses show locations of Ivrea defining the motion path of the Adriatic Plate with respect to Europe. Vertical hatching indicates Oligo–Miocene Adriatic crustal indenters, as explained in the text

the Periadriatic Fault amounted to some 150 km (Appendix, section A4.1.3). Calc-alkaline magmatism along the Periadriatic Fault System (Fig. 3) is attributed to Oligocene rupturing of the southeast-dipping European slab beneath the Alps (von Blanckenburg and Davies 1995, Rosenberg 2004) which by that time was long enough to rest partly in the mantle transition zone (Fig. 9a, b). We consider the position of the Periadriatic Fault at 35 Ma to mark the surface trace of the slab rupture beneath the Alps and assume that this rupture followed the subducted ocean–continent transition (Fig. 6) based on the expectation that this transition was a first-order rheological discontinuity. In the Dinarides, late Eocene to early Miocene subduction-related magmatism (Fig. 3) has been attributed to an eastward continuation of slab break off or mantle delamination beneath the Alps (e.g., Harangi et al. 2006). However, the distribution of these magmatic suites across the Dinarides indicates that they do not derive from melting of the European slab, but from the northeast-dipping Adriatic slab (Schefer et al. 2011 and discussion below).

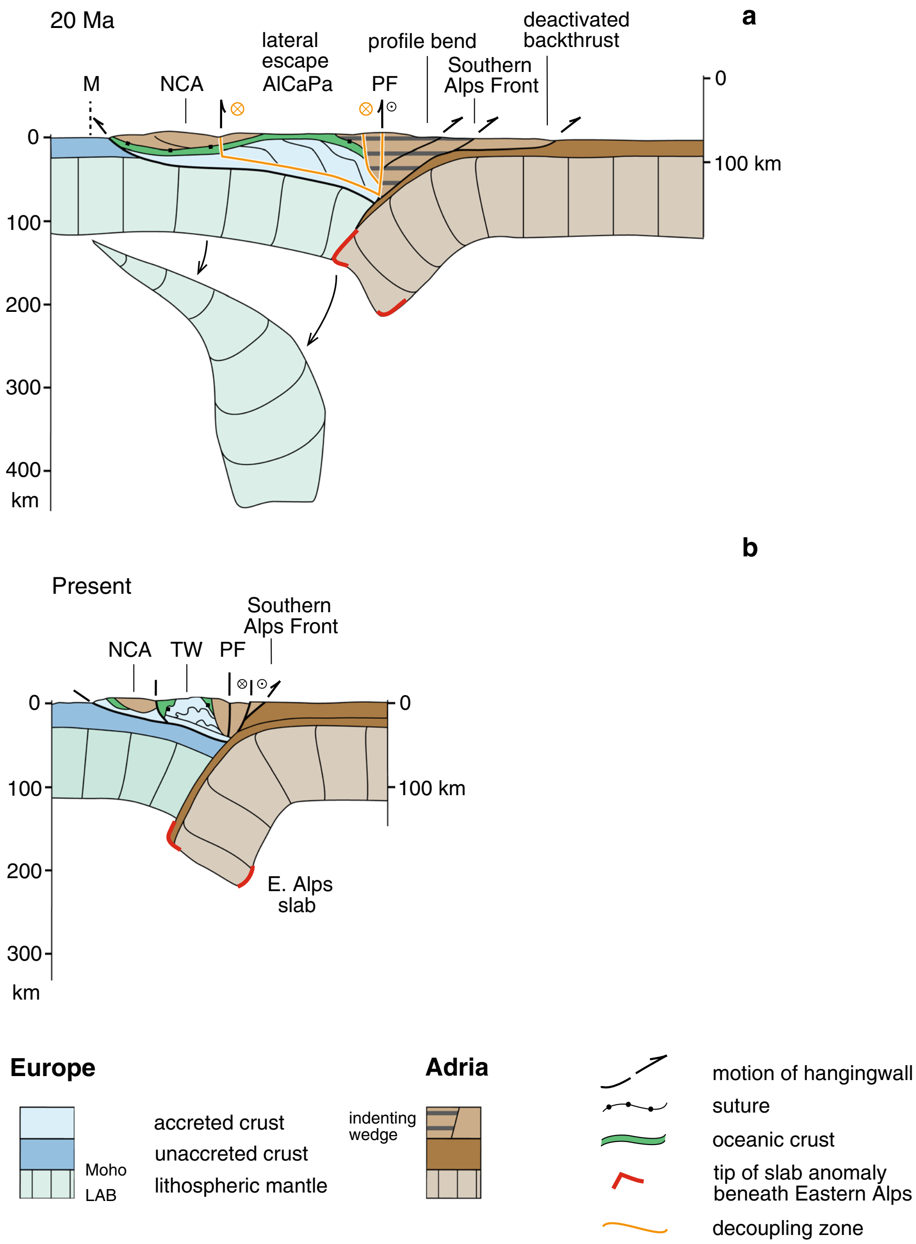


Fig. 11 Cross sections across the eastern part of the Alpine orogen from latest Eocene to Present: **a** 20 Ma: Indentation of eastern Adriatic crustal indenter, foundering of European slab, incipient northward subduction of Adriatic lithosphere derived from the Eastern and Southern Alps; **b** Present section at about 13°E with north-dipping Adriatic slab beneath the Tauern Window. Trace of cross sections in **a**, **b** shown, respectively, in Figs. 2 and 10

Shortening in the Western and Central Alps between 35 and 20 Ma accommodated an estimated 200 km of motion of Adria relative to Europe in the direction of convergence (N303°W, Fig. 8, see section A4.5). Within error, this value corresponds with the 180 km total length of European slab imaged in the ECORPS-CROP and NFP20E transects (Lippitsch et al. 2003, profiles A and B in their Fig. 13).

Second slab tearing and surface uplift in the Eastern Alps

A curious feature of the Eastern Alps is a late Eocene to early Oligocene peneplain (the “Dachstein paleosurface”) preserved in elevated karst plateaus of the Northern Calcareous Alps (Fig. 1) and sealed by Early Oligocene to earliest Miocene (30–21 Ma) terrestrial conglomerates and sandstones (Augenstein formation, Frisch et al. 1998, 2001). These authors interpreted these deposits to reflect a pronounced eastward decrease in Early Oligocene paleorelief going from mountains in the west to depocenters at the level of the Inntal basin and Molasse foreland basin in the central and eastern parts of the Eastern Alps (Frisch et al. 2001, their Fig. 7). This east–west paleo-topographic transition coincides spatially with the present slab gap between the Central and Eastern Alps (Fig. 4a). We propose that this gap was the site of a vertical tear in the downgoing European slab that nucleated in Early Oligocene to Early Miocene time (Kissling et al. 2003 and discussions with B. Fügenschuh), then propagated laterally to the northeast behind the retreating Carpathian subduction front in Miocene time. The trace of this second tear is depicted in map view in Fig. 6 by a curved arrow along the dotted line marked "≤30 Ma." The slab gap beneath the Eastern Alps also coincides approximately with the exhumed northeastern end of the Briançonnais continental sliver presently exposed in the Engadine Window (Fig. 2). This sliver originated in Jurassic time as an extensional allochthon of the European margin (Trümpy 1992; Schmid et al. 1990; Fig. 6) and was subducted in the Eocene (e.g., Berger and Bousquet 2008) just prior to the first slab-tearing event. The northeastern end of this continental sliver was therefore a mechanically viable place for the second tear to nucleate. We further speculate that by dividing the European slab into eastern and western segments, this tear allowed the eastern segment beneath the Eastern Alps to steepen and retreat northward while the western segment beneath the Central Alps continued to subduct south to southeastward in Neogene time (Kissling et al. 2003). Early Miocene detachment of the eastern European slab segment is expected to have triggered isostatic rebound, leading to Miocene uplift of the Dachstein paleo-erosional surface to its present altitude of 1,800–2,500 m in the Northern Calcareous Alps (Fig. 9c, Frisch et al. 2001).

"Wrong-way" subduction in the Eastern Alps, roll-back subduction in the Carpathians

Onset of northward Adriatic subduction in the Eastern Alps

The map and cross section at 20 Ma (Figs. 10, 11a) show the orogenic structure soon after the onset of northward indentation and subduction of Adriatic lithosphere beneath the Eastern Alps, as documented by Miocene south-vergent thrusting in the Southern Alps east of the GF (e.g., Doglioni 1987; Castellarin and Cantelli 2000; Schönborn 1999; Nussbaum 2000). This time also coincides with the onset of accelerated roll-back subduction in the Carpathians, marked by increased rates of clastic sedimentation in the externally migrating Carpathian foredeep (Sandulescu et al. 1981a, b; Morley 1996; Matenco and Bertotti 2000; Gągała et al. 2012), as well as by rifting, rapid subsidence and 22–8 Ma calc-alkaline magmatism in the Pannonian Basin (Fig. 3, e.g., Royden and Burchfiel 1989; Horváth et al. 2006; Pécskay et al. 2006; Seghedi and Downes 2011).

At 20 Ma, roll-back subduction was already well underway in the Apennines (Malinverno and Ryan 1986; Royden 1993; Doglioni et al. 1997; Faccenna et al. 2004; Molli 2008) and Hellenides (Le Pichon and Angelier 1979; Gautier and Brun 1994; Jolivet and Faccenna 2000; van Hinsbergen and Schmid 2012). This subduction was bounded to the north by the Alps–Apennines transfer fault (AAT, Fig. 10) which accommodated Oligocene-early Miocene WNW-directed thrusting along the Penninic Front in the Western Alps (PN in Fig. 10, Ceriani et al. 2001) overlapping in time with early-to-mid-Miocene SE-ward rifting and upperplate spreading of the Liguro-Provençal Basin (Séranne 1999) behind the eastwardly retreating Apenninic orogenic front (Molli et al. 2010). The reader is referred to the Appendix, sections A4.2 and A4.3, for a detailed discussion of the AAT and its kinematic relationship to the formation of the Western Alpine arc and the orogenic front in the northern Apeninnes.

The NW limit of Hellenic roll-back subduction in Miocene time is taken to be the Scutari-Peç Fault (SP in Fig. 10), which numerous authors (e.g., Kissel et al. 1995; van Hinsbergen and Schmid 2012) have proposed acted as a hinge zone between the unrotated Dinarides to the NW (e.g., de Leeuw et al. 2012) and the clockwise-rotated Hellenides to the SW (Kissel et al. 1995). Cenozoic-to-recent back-arc extensional faulting and calc-alkaline magmatism affected the Cenozoic nappe stack behind the retreating Hellenic trench (e.g., Burchfiel et al. 2008).

Change from Alps–Dinarides transfer faulting to Adriatic indentation and Carpathian roll-back subduction

The ADT2 was active until about 23–20 Ma, when strike-slip faulting initiated along the Mid-Hungarian Fault Zone (MH in Fig. 10, Csontos and Nagymarosy 1998; Fodor et al. 1998; Horváth et al. 2006). The Mid-Hungarian Fault Zone is depicted to be continuous with the northern part of the ADT2, which underwent more than 90° of clockwise rotation during indentation and north–south shortening. Tomljenović et al. (2008) report clockwise block rotations of up to 130°, probably late Oligocene–early Miocene in age, that re-oriented NW–SE trending Dinaric thrusts, including the West Vardar ophiolite front, into their present ENE–WSW trend (Fig. 10). The Mid-Hungarian Fault Zone transferred this deformation laterally to the northeast where it assumed the role of a stretching fault (Means 1989) that accommodated differential extension of the previously accreted Adriatic (AlCaPa) and European (Tisza–Dacia) crustal units as they rotated into the space opened by the eastward retreat and arcuation of the Carpathian orogen (Fig. 10, e.g., Csontos and Nagymarosy 1998; Fodor et al. 1998; Ustaszewski et al. 2008). Roll-back subduction of the Carpathian oceanic embayment and related Pannonian rifting in the upper plate of the orogen (e.g., Royden and Burchfiel 1989; Royden 1993) began no later than 20 Ma and ended at about 11 Ma as indicated by the youngest (Tortonian) deposits below the sole thrust of the Outer (External) Carpathians (Oszczypko et al. 2006). Pannonian extension migrated southeastward to sites of late- to post-collisional magmatism in the eastern Carpathians (Fig. 3, e.g., Seghedi and Downes 2011).

Interestingly, the onset of magmatism and rapid subsidence in the Pannonian Basin at 22–20 Ma preceded the beginning of subsidence in pull-apart basins in the Eastern Alps at 17 Ma that opened during lateral orogenic escape in the hangingwall of the Tauern Window (Scharf et al. 2013, their Fig. 9). This has been taken to indicate that lateral orogenic escape in the Eastern Alps was triggered by the "push" of Adriatic indentation rather than the "pull" of Carpathian roll-back subduction (Scharf et al. 2013, see discussion in section "Slab dynamics, mantle flow and decoupling in the Alps–Carpathian–Dinarides belt").

Separation of the western and eastern Adriatic indenters

The part of the Adriatic Plate immediately south of the Periadriatic Fault consists of continental lithosphere that experienced pre-Alpine metamorphism and only weak, low-temperature (<270 °C) Alpine metamorphic overprinting (Oberhänsli et al. 2004). Therefore, in Tertiary time this lithosphere was very strong, rendering it a semirigid indenter.

The Periadriatic Fault is the approximate surface trace of the indenter front and is offset sinistrally along the GF and the associated Giudicarie Thrust Belt (GF in Figs. 2, 10). The GF does not offset Moho depth contours (Spada et al. 2013) and is therefore interpreted to extend no further than to the base of the orogenic crust. It divides the leading edge of the Adriatic crust into two blocks: A western block (broadly hatched area in Fig. 10) whose lower crust wedged into the Central Alps and part of the arc of the Western Alps in the vicinity of the Ivrea Zone (Schmid et al. 1990, their Fig. 5; Rosenberg and Kissling 2013, their Fig. 1) and an eastern block of intermediate to lower continental crust (narrowly hatched area in Figs. 10, 11a) that indented the orogenic crust of the Eastern Alps (e.g., Ratschbacher et al. 1989, 1991a, b, Rosenberg et al. 2007).

The timing of indentation of the eastern block is constrained by the age of its bounding faults, which are marked GF, SA and MH in Fig. 10. Zircon and apatite fission-track ages along the GF constrain its motion to have begun in late Oligocene–Early Miocene time (Pomella et al. 2012). Biostratigraphic criteria along the Giudicarie Thrust Belt (Luciani and Silvestrini 1996) indicate that the main phase of sinistral transpression lasted from about 23–21 Ma (Schmid et al. 2013; Scharf et al. 2013) to 7 Ma based on the lateral continuation of this thrust belt to the southwest into the subsurface Milan Thrust (MT in Fig. 2) which is sealed by Messinian sediments (e.g., Pieri and Groppi 1981; Schönborn 1992). The onset of Giudicarie faulting and thrusting also coincided with the beginning of post-Dinaric, predominantly south-directed thrusting along the Southern Alps Front (SA in Figs. 2, 10), as cited above. The eastern end of this thrust front in northern Slovenia and northern Croatia in the vicinity of the Medvednica mountains (Me in Figs. 2, 10) merges with a zone of Mio-Pliocene thrusting, dextral strike-slip faulting and block rotations (Fodor et al. 1998; Vrabec and Fodor 2006; Tomljenović et al. 2008), and yet further to the east, with strike-slip duplexes along Mid-Hungarian Fault Zone (MH in Fig. 10; Fodor et al. 1998). To maintain kinematic compatibility, we link the Miocene thrust front in the Southern Alps to a northern continuation of the dextrally transpressive Split-Karlovac Fault (Chorowicz 1970, 1975) which we propose transferred most of the Miocene shortening in the Southern and Eastern Alps to the Miocene orogenic front in the southern External Dinarides (Fig. 10). The Split-Karlovac Fault crosscuts Paleogene Dinaric structures and was active in Miocene time as constrained by deformed early–middle Miocene lacustrine deposits along the fault (de Leeuw et al. 2012; Appendix section A3.6).

Indentation of the western block involved coeval WNW-directed thrusting and S- to SE-directed backfolding of Penninic units in the Western Alps beginning in late Eocene–early Oligocene time and ending at about 16 Ma (e.g., Schmid et al. 1996; Ceriani et al. 2001; Ceriani and Schmid 2004; Handy et al. 2005 and references therein). In the Central Alps, north–south shortening related to wedging of the Adriatic lower crust post-dated 31 Ma (Rosenberg and Kissling 2013) and occurred mostly from 21 to 16 Ma (Schönborn 1992; Schiunnach et al. 2010). Thus, indentation of the western block overlapped in time with indentation of the eastern block bounded by the GF (Pomella et al. 2012).

Taken together, these relationships indicate that in early Miocene time the leading edge of the Adriatic Plate east of the GF moved northward relative the western part which had already begun to indent the Western and Central Alps some 10 Ma earlier. We will return to this point in section "Kinematics of Adriatic subduction and crustal indentation in the Alps" when considering the mechanism of indentation and northward subduction beneath the Eastern Alps.

Origin of the slab anomaly beneath the Eastern Alps

Several lines of reasoning cast doubt on the classical concept of uninterrupted southeastward subduction of European lithosphere beneath the Eastern Alps, as discussed above and at length in Part C of the Appendix. Yet, if the slab is not European in origin, then how we can we explain the only alternative, namely that it is Adriatic lithosphere?

To understand where the slab anomaly beneath the Eastern Alps originated, we tracked its position with respect to the crustal structure back in time to 84 Ma. In all reconstructions, the surface trace of the slab's leading edge comes to rest just north of the Periadriatic Fault (Figs. 5, 6, 8, 10). The proximity of the restored Eastern Alps slab to post-20 Ma, south-directed thrusting of the Mesozoic sedimentary cover in the Southern Alps east of the GF (Fig. 10) suggests that the slab comprises the substratum of these detached units. The lack of ophiolites in the Southern Alps obviates the presence of oceanic lithosphere in the downgoing slab, effectively precluding scenarios that invoke subduction of Neotethys as a part of this slab (Lippitsch et al. 2003). The slab is therefore inferred to comprise cold and thick (≥100 km) subcontinental mantle and lower continental crust. During the counterclockwise rotation of Adria, these units subducted to the north–northwest under the laterally extruding orogenic crust in the Eastern Alps (Fig. 10).

Teleseismic tomography indicates that the $+V_p$ anomaly beneath the Eastern Alps is round in map view at 210–240 km depth (section "Restoring the Alpine slabs," Figs. B1b and c, Lippitsch et al. 2003) and may be connected eastward to a deeper $+V_p$ anomaly at 350–600 km under the Pannonian Basin (Dando et al. 2011). The shortening implied by this large amount of slab material exceeds the measured Miocene north–south shortening in the eastern part of the Southern Alps [minimum of 50 km according to Schönborn (1999) and Nussbaum (2000), see Fig. A1a] and is also less than the 190 km of shortening predicted by assuming that the Adriatic plate experienced a counterclockwise rigid-body rotation of 20° with respect to Europe since early Miocene time (Ustaszewski et al. 2008). If the anomalous length and shape of the eastern end of the Eastern Alps slab (Fig. B1c) are real rather than mere artifacts of tomography, then a possible explanation is that the slab stretched and deformed (Mitterbauer et al. 2011). This deformation occurred either under its own weight and/or as it was pulled or sucked down by the adjacent slab of European lithosphere that foundered and then tore off to the northeast during northeastward Miocene roll-back subduction in the Western Carpathians. Another possibility is that the northeastern end of the Eastern Alps slab in excess of 200 km length (Figs. B2c, d) is an amalgamation of the Adriatic and European slabs, with the excess length representing a segment of torn, Oligocene to early Miocene European slab that, in the images of Dando et al. (2011, their Figs. 10, 12), descends to the mantle transitional zone.

Kinematics of Adriatic subduction and crustal indentation in the Alps

Neogene subduction of a fragment of the Adriatic lithosphere beneath the Eastern Alps was only possible once it decoupled laterally from adjacent Adriatic lithosphere to the west and east. As discussed in the section "Separation of the western and eastern Adriatic indenters," lateral decoupling of the eastern Adriatic crustal block or wedge from the western Adriatic lower crustal wedge along the GF began in early Miocene time. Sinistral displacement along this fault was not transferred to the northern thrust front of the Alps, where only minor deformation has been recorded since 20–15 Ma (Ortner et al. 2011), but was instead accommodated in the core of the orogen by upright folding, extensional exhumation and eastward lateral stretching of Europe-derived orogenic crust exposed in the Tauern Window (Rosenberg and Berger 2009). A northward indentation direction in the Eastern Alps is inferred from analog-modeling studies (Ratschbacher et al. 1991b; Rosenberg et al. 2007) and slip-line analysis of post-nappe folds and shear zones in the Tauern Window (Handy et al. 2005).

In the east, we propose that the ADT2 was the locus of lateral decoupling in late Eocene–early Oligocene time (Fig. 8), when collision began in the Alps and when the Adria–Europe convergence rate slowed from 15 mm/year before 35 Ma to 6 mm/year, according to the Adriatic motion path in this study. This decoupling enabled subduction of the Adriatic slab fragment beneath the Eastern Alps beginning in early Miocene time, in agreement with the onset of south-directed thrusting in the eastern Southern Alps as well as with motion along the Giudicarie and Split-Karlovac faults. The much larger segment of Adriatic slab to the southeast of the ADT2, beneath the northern Dinarides, is believed to have delaminated (Schefer et al. 2011) or ruptured in response to the reduction in Adria–Europe convergence rate, and to have undergone partial melting as evidenced by 37–22 Ma calc-alkaline magmatism in accreted Adriatic and European units forming the upper plate of the Dinaric orogen (Fig. 3). Partial melting would reduce the mantle viscosity by several orders of magnitude (Rosenberg and Handy 2005), more than enough to enhance lateral decoupling along the ADT2 and to facilitate asthenospheric upwelling along the tear in the Adriatic slab. This upwelling may have thermally eroded the slab beneath the Dinarides, partly accounting for the currently imaged slab gap there (Fig. 4d, section "Slab dynamics, mantle flow and decoupling in the Alps–Carpathian–Dinarides belt").

Relating the kinematics of Adriatic subduction beneath the Eastern Alps to crustal indentation tectonics is not straightforward, given that the restored early Miocene location of the slab tip lies just north of the Periadriatic Fault and to the east of pronounced crustal indentation in the Tauern Window area (Fig. 10). There, the indenter front is situated at the northern boundary of a triangular block of rigid Austro-alpine crust which fragmented into two sub-indenters during north-directed indentation (Linzer et al. 2002; Scharf et al. 2013). Together with the restored slab tip, this crustal wedge defines the northern limit of the nascent eastern Adriatic indenter in early Miocene time, as depicted in Fig. 10.

The absence of a slab beneath the western part of the Tauern Window (Fig. 4a, and B2b) and the contrasting post-20 Ma motions of the crustal indenter (to the north) and the Eastern Alps slab (counterclockwise and to the north–northwest) necessitate one or more detachment surfaces between the crustal indenter and the downgoing slab. This putative detachment system allowed counterclockwise rotation and subduction of Adriatic lithospheric mantle and lower crust into the space beneath the Eastern Alps opened by Oligocene rupturing and foundering of the European slab (Fig. 11). We speculate that rotation of the slab during subduction caused it to steepen and curl, thus acquiring its present subvertical dip in the west and its oblique trend with respect to the surface structures in the Tauern Window (Fig. B1) while maintaining a moderately northeastward dip at its eastern end (Fig. B2d).

Widespread horizontal decoupling at the crust–mantle boundary and/or within the crust during subduction helps explain several anomalous structures related to indentation in the Eastern and Southern Alps. First, horizontal decoupling beneath the Tauern Window area probably localized at or just above the tip of the crustal wedge, facilitating the preservation of the pre-Miocene, S-dipping European Moho below this wedge as imaged in the TRANSALP section (Kummerow et al. 2004; Lüschen et al. 2004, 2006). Furthermore, it allowed the overlying AlCaPa orogenic crust to extrude laterally to the east, subperpendicular to the direction of convergence and indentation (Oldow et al. 1990). Finally, horizontal decoupling may also explain the change in the style and location of Miocene north–south crustal shortening along strike of the eastern Adriatic indenter: At the western end of this indenter, shortening was greatest north of the Periadriatic Fault and in front of the crustal wedge in the Tauern Window area, whereas at the eastern end, i.e., south of the slab's leading edge, Mio-Pliocene shortening was accommodated primarily south of the Periadriatic Fault and involved a combination of thrusting, strike-slip faulting and clockwise block rotations, as noted above for the Medvednica area.

The subsurface trace of Miocene subduction in the Eastern Alps is possibly still seen today east of the Tauern Window, where recent geophysical investigations reveal that the Moho is undefined between 12°E and 15°E (white zone of missing Moho depth contours in Spada et al. 2013, see their Fig. 11). This zone is characterized by high V_p values (7–8.2 km/s) and a low-velocity gradient (0.08 s^{-1}) across the crust–mantle transition (Diehl et al. 2009); the location and slight obliquity of this zone with respect to the Periadriatic Fault corresponds closely with that of the horizontalized edge of the Eastern Alps slab prior to subduction. We speculate that this zone of undefined Moho represents an anomalous volume of detached lower crustal and/or upper mantle rock that accumulated first during south-directed late Paleogene subduction of European lithosphere, and again during north-directed Miocene subduction of Adriatic lithosphere.

Forces driving northward subduction of Adriatic continental lithosphere in the Alps

Subducting Adriatic continental lithosphere to a depth of 200 km or more beneath the Eastern Alps is controversial on dynamic grounds, especially because we have argued that the slab was not attached to oceanic lithosphere, which is usually considered necessary to provide the negative buoyancy to pull a slab down. However, there is circumstantial evidence that the slab was pushed more than pulled beneath the Eastern Alps. Adria converged with Europe at a rate of about 0.6–1 cm/year in Neogene time as estimated from shortening values in north–south transects of the Central and Eastern Alps (Rosenberg and Berger 2009). These rates are comparable within error to Africa's northward motion at about 1 cm/year during the same period (van Hinsbergen et al. 2011), suggesting that Neogene motion of the Adriatic Plate, including its counterclockwise rotation relative to Europe (e.g., Márton et al. 2011), was driven by impingement of the African Plate. Once the northern front of the Adriatic Plate was fragmented, the full force of indentation ultimately driven by Africa was concentrated on the relatively small volume of laterally decoupled lithosphere in the eastern part of the Southern Alps, thus increasing the stress that pushed the slab down to the north beneath the Eastern Alps.

In addition, geodynamic modeling has shown that continental subduction is possible where the crust, especially the lower crust, is thin and the underlying lithospheric mantle is sufficiently cold and thick to render it neutrally, or even negatively buoyant (Capitanio et al. 2010; Afonso and Zlotnik 2011). All of these conditions are met by the Southern Alpine lithosphere, which has a very dense lower crust comprising Paleozoic granulite-facies rocks (e.g., Ivrea Zone: Fountain 1976; Zingg et al. 1990) and which was severely attenuated during Early Mesozoic rifting (Bernoulli et al. 1990, 2003; Handy and Zingg 1991; Handy et al. 1999; Manatschal et al. 2007). The time between the end of rifting of the Adriatic margin (c. 170 Ma) and the onset of northward subduction in the Eastern Alps (20 Ma) was sufficient to develop a thermally mature lithosphere with a thickness of about 100 km. These factors all contributed to rendering the continental lithosphere in the Southern Alps prone to subduction.

Hyper-extended, magma-poor margins and ocean–continent transitions like those preserved in the Alps were probably a general feature of Alpine Tethys in Cenozoic time and were characterized by thick, depleted subcontinental mantle underlying thin extensional allochthons of continental crust (Lemoine et al. 1987; Desmurs et al. 2001). The neutral to negative buoyancy of such old transitional crust (70–90 My old at the onset of Alpine Tethyan subduction) perhaps explains why continental lithosphere makes up almost half of the total subducted material in the Alpine–Mediterranean domain as estimated by comparing plate reconstructions with teleseismic tomographic images down to the mantle transitional zone (Handy et al. 2010).

Slab dynamics, mantle flow and decoupling in the Alps–Carpathian–Dinarides belt

How did motion of the mantle affect crustal dynamics, especially during the switches in subduction polarity in the Alps? To answer this question, we constructed slab motion maps (Fig. 12) by extrapolating slab lengths back in time according to the rates and duration of subduction used in the paleotectonic maps above. Figure 12 shows the position of the orogenic fronts with respect to the subduction of the European (blue) and Adriatic (yellow) lithospheric mantle, as well as asthenospheric upwelling (orange), magmatism (red dots) and mantle flow (red arrows). In all time slices before 20 Ma, the future slab beneath the Eastern Alps occupied the upper plate of the Alpine orogen, above the downgoing European slab (Fig. 12a–c).

Slab tearing in response to late Paleogene Adria–Europe collision (Fig. 12a, b) was instrumental in preconditioning the mantle for the dramatic segmentation, expansion and arcuation of the Alpine orogenic belt during what we term the Neogene Alpine revolution (Fig. 12c, d). Tears in the oppositely dipping slabs beneath the Alps and Dinarides weakened and eventually severed the lithosphere along the ADT2 (Fig. 12a) which, together with its predecessor, the ADT1, had linked the Alpine and Dinaric subduction zones since at least Late Cretaceous time (Figs. 5, 6). This tearing detached the Adriatic Plate from its pre-late Eocene slab beneath the Dinarides and concentrated the force of Adria–Europe convergence at its hard northern edge in the Alps, leading to crustal wedging and indentation. Continued motion of the Adriatic Plate to the northwest, away from the foundering Dinaric segment of the Adriatic slab, opened a lithospheric gap along the defunct ADT2 that we speculate was filled by upwelling asthenosphere (Fig. 12b–d). Heat advection associated with this upwelling is expected to have partly melted the foundering slabs (von Blanckenburg and Davies 1995; Harangi et al. 2006), generating the observed Eo-Oligocene calc-alkaline magmatism in the Alps and Dinarides (Fig. 3).

In the Ligurian area, the switch from Alpine to Apenninic subduction polarity sometime between 35 and 30 Ma (not shown in Fig. 12b) was probably induced by the resistance to further subduction of European continental lithosphere and facilitated by the presence of old (c. 100 Ma), negatively buoyant eastern Ligurian oceanic lithosphere in the upper plate of the Alpine orogen (Handy et al. 2010). With this reversal in subduction polarity, the western segment of the Alpine orogen became part of the upper plate of the Apenninic orogen, while the rest of the Alps north of the Alps–Apennines Transfer Fault (AAT in Fig. 12b) continued to accrete during northwest-directed Adriatic indentation. Roll-back subduction is characterized by overall lithospheric tension due to the downward pull of the slab (e.g., Elsasser 1971; Forsyth and Uyeda 1975; Conrad and Lithgow-Bertelloni 2002). Thus, the onset of Apenninic subduction weakened the western boundary of the Adriatic Plate and, together with the previous slab detachment and decoupling along the ADT2 in the east, was instrumental in allowing the Adriatic Plate to rotate counterclockwise in response to the northwestward push of the much larger African plate (Fig. 12c). Apenninic roll-back subduction consumed not just the eastern Ligurian oceanic lithosphere but large volumes of the western Adriatic margin (Handy et al. 2010), indicating that the rate of this subduction must have been faster than the average rate of Miocene counterclockwise rotation of the Adriatic Plate. The difference in Adriatic subduction and rotation rates was probably accommodated in part by sinistral shearing along the early Miocene–Pliocene AAT which, as noted above, overlapped in time with Oligo–Miocene Adriatic indentation and wedging of the Alpine orogenic edifice (Appendix, section A4.3).

At no later than 20 Ma, the lower crust and mantle of the upper plate of the Paleogene Alpine orogen between the GF and the ADT2 began to subduct northward into the void left by the ruptured European slab (Fig. 12c). Adria indented north to northwestward into the orogenic edifice of the Eastern Alps (Schmid et al. 2004; Bousquet et al. 2008; Handy et al. 2010) while the Carpathian segment of the Alpine–Carpathian orogen expanded to the north and east into the Carpathian oceanic embayment of Alpine Tethys (Fig. 12c, d). Similarly, the Apenninic and Hellenic subductions retreated into old oceanic lithosphere, respectively, of the eastern Ligurian branch of Alpine Tethys (e.g., Malinverno and Ryan 1986; Faccenna et al. 2004) and the southern branch of Neotethys (e.g., Stampfli and Borel 2002; Speranza et al. 2012), thereby consuming the Adriatic Plate from both sides (Fig. 12c, d). Royden and Burchfiel (1989) were the first to point out the striking difference between "hard" collision involving deep continental subduction, massive accretion of the lower plate, and Molasse-type foredeep sedimentation in the Alps, and "soft" collision featuring modest accretion, subdued relief, an underfilled marine foredeep and upper plate extension

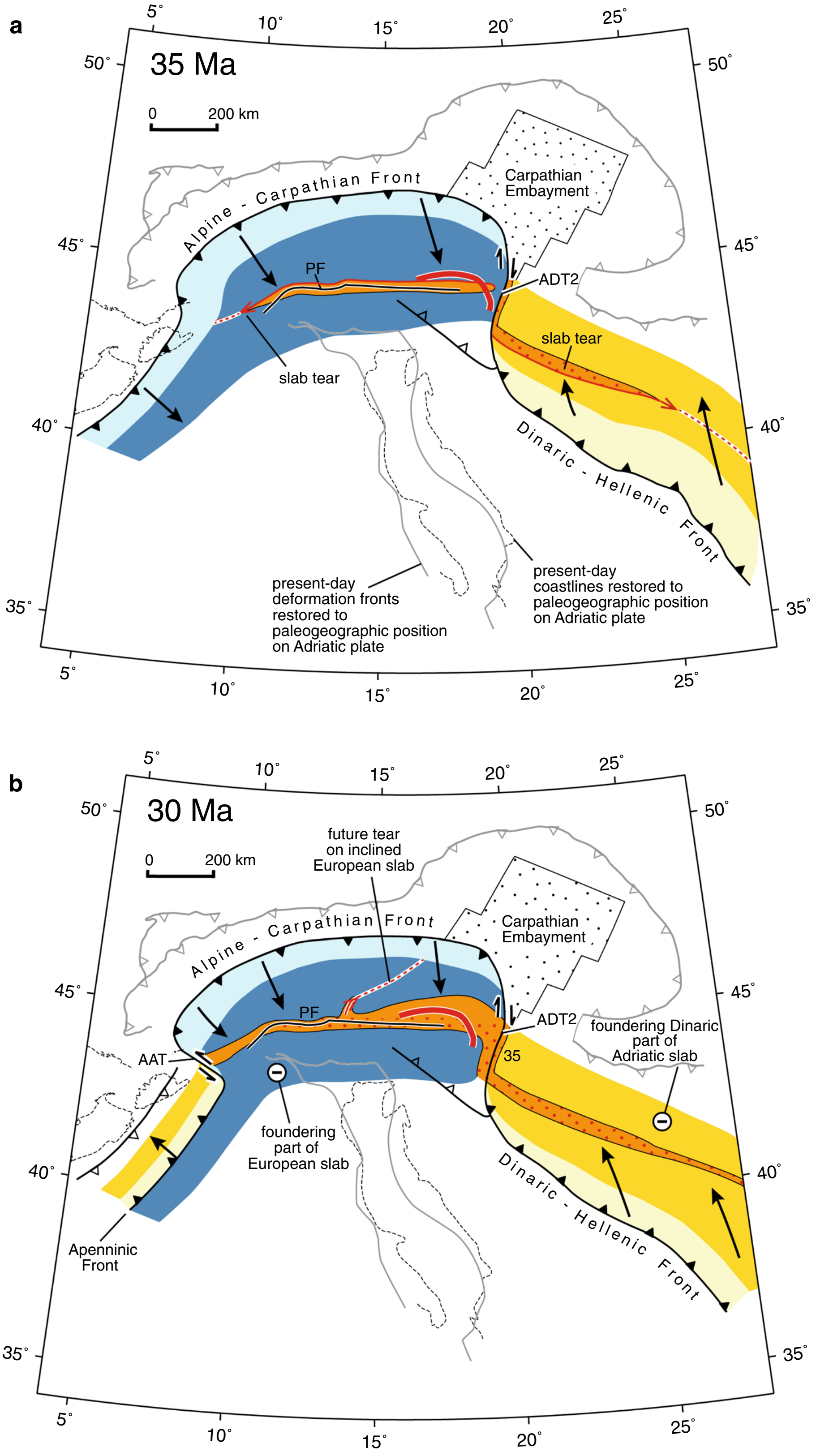


Fig. 12 Slab maps for the Alpine chain with upper plates removed and only major faults shown. **a** 35 Ma: Rupturing of Adriatic and European slabs, respectively, beneath the Dinarides and Alps, leads to asthenospheric upwelling and magmatism; **b** 30 Ma: foundering of the European and Adriatic slabs triggers magmatism; incipient delamination and tearing of the remaining European slab beneath the Eastern Alps; **c** 20 Ma: Asthenospheric upwelling and flow, onset of northward subduction beneath the Eastern Alps, eastward orogenic escape in the Eastern Alps, roll-back subduction in Carpathians; **d** 10 Ma: Continued northward subduction of Eastern Alps slab, eastward orogenic escape into the Pannonian Basin, asthenospheric flow to beneath the Pannonian Basin, thermal erosion of Adriatic slab beneath Dinarides; **e** Present: Northward subduction of Adriatic lithosphere beneath Eastern Alps and shortening of the Pannonian Basin. Arrows indicating mantle flow are adopted from Jolivet et al. (2009, their Fig. 2a). Abbreviations used as in maps above

Fig. 12 continued

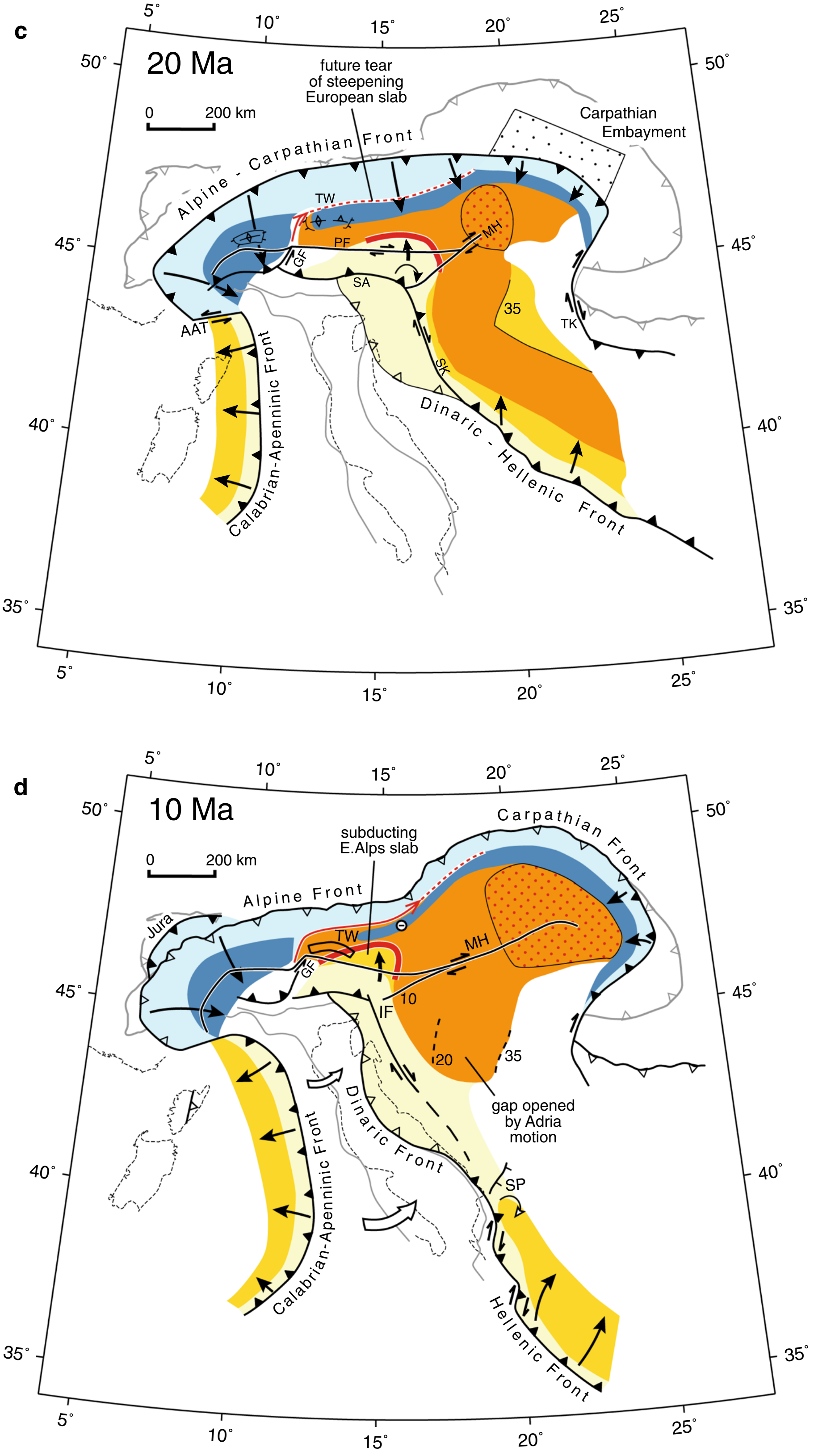
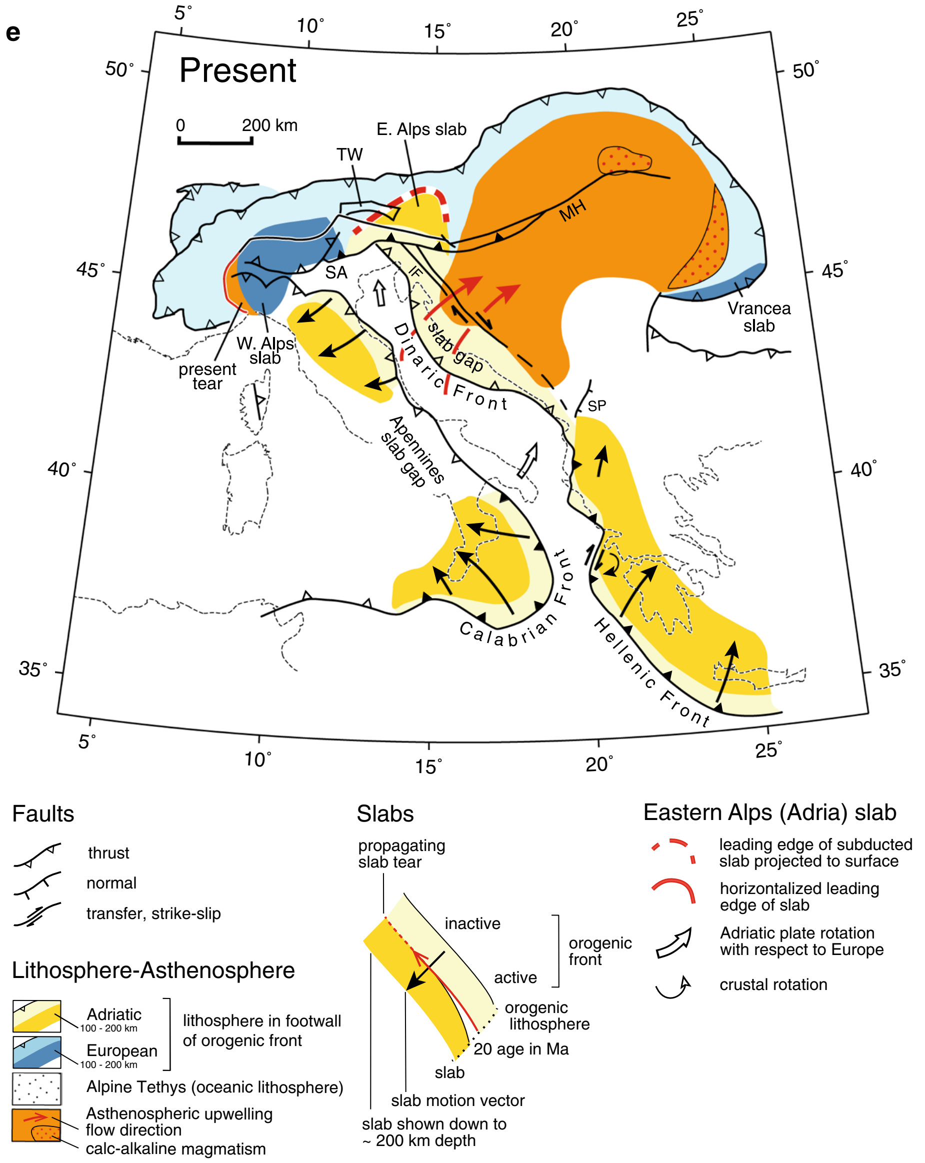


Fig. 12 continued



in the Carpathians. The eastward "in-sequence" propagation of Carpathian foredeep sedimentation and thrusting combined with the general southeastward younging of Miocene magmatism in the Pannonian Basin (Figs. 3, 12c, d; Konečný et al. 2002; Harangi et al. 2006; Pécskay et al. 2006; Seghedi and Downes 2011 and refs. therein) is diagnostic of roll-back subduction (Royden and Burchfiel 1989; Royden 1993; Horváth et al. 2006) and effectively precludes mechanisms that involve subvertical delamination and downwelling of gravitationally unstable lithospheric mantle (e.g., Dando et al. 2011).

Roll-back subduction in the Carpathians must have been accompanied by substantial asthenospheric flow, both upward as well as around the retreating slabs (Konečný et al. 2002) to fill the space beneath the extending Pannonian lithosphere. SKS fast splitting directions of shear waves beneath the northern Dinarides in the vicinity of the present slab gap (red arrows in Fig. 12e adapted from Jolivet et al. 2009) are interpreted to track such flow from beneath the Adriatic Plate through the Dinaric slab gap to beneath the Pannonian Basin. This flow is subparallel to the direction of Miocene extension in the Tisza block (Fig. 10), but the age and rates of mantle flow are unconstrained. It is therefore unresolved whether this flow actively assisted Pannonian extension, or whether the asthenosphere was dragged by the extending lithosphere.

The broadly coeval onset of Adriatic indentation and rapid Pannonian extension in early Miocene time (Horváth et al. 2006) has fueled speculation that Adriatic indentation and Carpathian orogenesis were dynamically linked, either in that "pull" of Carpathian roll-back subduction drove eastward lateral escape in the Eastern Alps (e.g., Fodor et al. 1998), or vice versa, that “push” of the thick orogenic crust in the Eastern Alps drove eastward subduction of the Carpathian oceanic embayment. Yet, rifting in the Pannonian Basin preceded the onset of east–west extension of the Eastern Alps by some 3–4 My (section “Change from Alps–Dinarides transfer faulting to Adriatic indentation and Carpathian roll-back subduction”), limiting the role of Carpathian roll-back subduction to that of enhancing rather than triggering lateral orogenic escape of the Eastern Alps (Scharf et al. 2013).

We believe that the link between “wrong-way” Adriatic continental subduction, indentation and Carpathian roll-back subduction involved the interplay of disparate forces that were preconditioned by slab tearing in the Alps and Dinarides. These tearing events and the related rise of asthenosphere into the widening lithospheric gap along the former ADT2 (Fig. 12c, d) weakened the upper plate of the Carpathian segment of the Alpine orogen, thereby reducing the resistance to the pull of roll-back subduction of the oceanic embayment. Meanwhile in the Alps, the northward push of Africa was concentrated along the hard northern edge of the Adriatic Plate, thus promoting northward indentation of its upper crust, while its mantle and lower crust were subducted. Thus, lateral escape of decoupled Eastern Alpine orogenic crust in response to this indentation is unlikely to have provided a direct mechanical link between the Alps and Carpathians.

Today, the Vrancea slab anomaly (Fig. 12e) represents the final vestige of subducted European lithosphere still attached to the crust in the Carpathians. It hangs vertically beneath the foredeep of the southeastern Carpathians (e.g., Girbacea and Frisch 1998; Spakman and Wortel 2004), well to the east of late- to post-collisional andesitic volcanics (Fig. 3) and flysch deposits that mark the end of roll-back subduction (Fig. 12e).

In conclusion, the Alpine chain owes its complex three-dimensional structure to a combination of along-strike variations in the structure of the Tethyan margins and basins, and to widespread decoupling of lithospheric mantle from orogenic crust in the Eastern Alps and Carpathians in Miocene time. The old age of the Tethyan oceanic lithosphere at the time of subduction plus the reduction in Adria–Europe convergence rate at the onset of Alpine collision rendered the slabs gravitationally unstable and therefore prone to rupture and reversals in subduction polarity.

Acknowledgments Many friends and colleagues have supported the development of this paper, which began during the first author’s sabattical in the fall of 2011. Participants of the 2nd MedMeet in Berlin (November 2013), especially Claudio Faccenna, László Fodor, Bernhard Fügenschuh, Laurent Jolivet, Ferenc Horváth, Liviu Matenco, Douwe van Hinsbergen and Rinus Wortel, are thanked for lively discourse that sharpened our thinking on several key issues. We are indebted to Stefan Schmid for use of his compilation of Neogene shortening estimates in the Alps, as well as for many discussions and written critique of earlier versions of our reconstructions. Ferenc Horváth, Giancarlo Molli, Jon Mosar and Adrian Pfiffner generously provided information and comments, respectively, on the Pannonian Basin, northern Apennines, Molasse Basin and Helvetic Nappes. We also benefited from fruitful discussions with Claudio Rosenberg on the Eastern Alps, with Eline Le Breton on plate motions in the Western Mediterranean, as well as with other members of the tectonics group in Berlin: Audrey Bertrand, Silvia Favaro, Peter Gipper, Friedrich Hawemann, Andreas Scharf and Susanne Schneider. Martina Grundmann (Berlin) patiently assisted in preparing the figures. Finally, we thank Clark Burchfiel and especially Bernhard Fügenschuh for their critical reviews, and the chief editor, Christian Dullo, for his support in getting our manuscript into print. This paper integrates the results of several DFG projects over the years (HA-2403/3, 5, 8; RO-2177/4, 5) which are duly acknowledged.

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