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Lithospheric Evolution of Cenozoic UHP Terranes: From Convergence to Extension

Key Points:

- A specific geologic record for each different exhumation mechanism
- An integrated tectonic reconstruction for the Alpine and Apenninic subductions
- Synconvergent exhumation models are not consistent with Mediterranean geology

Supporting Information:

- Supporting Information S1

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Contrasting styles of (U)HP rock exhumation along the Cenozoic Adria-Europe plate boundary (Western Alps, Calabria, Corsica)

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Abstract Since the first discovery of ultrahigh pressure (UHP) rocks 30 years ago in the Western Alps, the mechanisms for exhumation of (U)HP terranes worldwide are still debated. In the western Mediterranean, the presently accepted model of synconvergent exhumation (e.g., the channel-flow model) is in conflict with parts of the geologic record. We synthesize regional geologic data and present alternative exhumation mechanisms that consider the role of divergence within subduction zones. These mechanisms, i.e., (i) the motion of the upper plate away from the trench and (ii) the rollback of the lower plate, are discussed in detail with particular reference to the Cenozoic Adria-Europe plate boundary, and along three different transects (Western Alps, Calabria-Sardinia, and Corsica-Northern Apennines). In the Western Alps, (U)HP rocks were exhumed from the greatest depth at the rear of the accretionary wedge during motion of the upper plate away from the trench. Exhumation was extremely fast, and associated with very low geothermal gradients. In Calabria, HP rocks were exhumed from shallower depths and at lower rates during rollback of the Adriatic plate, with repeated exhumation pulses progressively younging toward the foreland. Both mechanisms were active to create boundary divergence along the Corsica-Northern Apennines transect, where European southeastward subduction was progressively replaced along strike by Adriatic northwest-ward subduction. The tectonic scenario depicted for the Western Alps trench during Eocene exhumation of (U)HP rocks correlates well with present-day eastern Papua New Guinea, which is presented as a modern analog of the Paleogene Adria-Europe plate boundary.

1. Introduction

Since the revolutionary discovery of ultrahigh pressure (UHP) rocks in the Dora-Maira of the Western Alps [*Chopin*, 1984], the exhumation of (U)HP rocks remains one of the most exciting and controversial topics in Earth Sciences [e.g., *Platt*, 1993; *Ernst et al.*, 1997; *Carswell and Compagnoni*, 2003; *Jolivet et al.*, 2003; *Hacker et al.*, 2006; *Agard et al.*, 2009; *Guillot et al.*, 2009a; *Liou et al.*, 2009; *Gilotti*, 2013; *Warren*, 2013]. Many different mechanisms have been proposed to explain how buoyant (U)HP rocks travel back to the surface following subduction to depths even >100 km [e.g., *von Blanckenburg and Davies*, 1995; *Maruyama et al.*, 1996; *Boutelier and Chemenda*, 2008; *Webb et al.*, 2008; *Beaumont et al.*, 2009; *Ellis et al.*, 2011]. Most popular models, such as the channel-flow model [*Beaumont et al.*, 2001; *Godin et al.*, 2006], assume a stationary trench and fixed boundaries within the subduction zone, which requires removal of the overlying rock pile by erosion/tectonics or forced circulation in a low-viscosity wedge [e.g., *Chemenda et al.*, 1995; *Zeitler et al.*, 2001; *Gerya et al.*, 2002; *Yamato et al.*, 2008]. However, erosional removal of overlying cover to exhume (U)HP rocks is often contradicted by the negligible amount of synexhumational detritus [e.g., *Krabbendam and Dewey*, 1998; *Taylor et al.*, 1999; *Zhang et al.*, 2002; *Garzanti and Malusà*, 2008]. In addition, forced circulation in a low-viscosity wedge is often contradicted by the strength and coherence of the exhumed nappe pile, which often preserves precollisional structures [*Jolivet et al.*, 2003; *Manatschal*, 2004]. Alternative exhumation models have thus been proposed, which consider boundary divergence within the subduction zone to explain exhumation of coherent (U)HP units even in cases where the stratigraphic record suggests that erosion was minor. These models are the motion of the upper plate away from the trench [*Malusà et al*., 2011a], and the rollback of the lower plate [*Jolivet et al*., 1994; *Brun and Faccenna*, 2008; *Lister and Forster*, 2009].

In this paper, we discuss such boundary divergence exhumation models with particular reference to the Cenozoic Adria-Europe plate boundary in the western Mediterranean, by combining geologic evidence with plate motion and tomography constraints. We integrate petrologic, structural, and stratigraphic data from the Western Alps [*Malusà et al*., 2011a] with available data from the Apennines and Corsica, and provide the first integrated reconstruction of the Alpine and Apenninic subduction zones within the framework of the recent palinspastic reconstructions proposed for this plate boundary area [*Malusà et al*., 2015]. Geologic observations are compared with predictions derived from fixed-boundary models of synconvergence exhumation recently applied to the Western Alps [*Butler et al*., 2013; *Jamieson and Beaumont*, 2013]. We then compare (U)HP exhumation in the Western Alps with available constraints from the (U)HP units of eastern Papua New Guinea in the southwestern Pacific [*Davies and Warren*, 1992; *Baldwin et al*., 2008], and suggest that this region provides a modern analog for the Paleogene Adria-Europe plate boundary.

2. Divergence in Subduction Zones: Upper Plate Motion Versus Slab Rollback

Fixed-boundary models, including a stationary trench, are widely applied to explore (U)HP rock exhumation during subduction and orthogonal convergence between upper and lower plates. One of the major implications of fixed-boundary exhumation models (Figure 1, case (i)) is the major role played by erosion [e.g., *Beaumont et al*., 2001; *Zeitler et al*., 2001]. As a consequence, during (U)HP rock exhumation, massive volumes of orogenic detritus eroded from the overlying accretionary wedge is predicted to be deposited in sedimentary basins surrounding the orogen. This sediment includes HP clasts, and is generally accreted at the toe of the wedge and underplated (Figure 1c, case (i)). Figure 2 illustrates a recent attempt of application of this category of models to the Western Alps [*Butler et al*., 2013; *Jamieson and Beaumont*, 2013]. However, these models are generally unable to reproduce the observed stratigraphic and petrologic evidence, as explained in more detail in the next sections.

On the other hand, two alternative end-member mechanisms may lead to divergence in accretionary wedges, leading to exhumation of (U)HP rocks in cases where the stratigraphic record is supportive of a minor role played by erosion. These mechanisms are: the motion of the upper plate away from the trench (Figure 1, case (ii)); and the retreat of the subduction hinge, also referred to as slab rollback (Figure 1, case (iii)). In case (ii), exhumation is controlled by the motion of the upper plate, whereas in the case (iii) it is controlled by motion (rollback) of the lower plate [*Dewey*, 1980; *Brun and Faccenna*, 2008; *Malusà et al*., 2011a]. Both of these mechanisms result in removal of a tectonic lid, allowing for the exhumation of more buoyant rocks from HP or UHP depths.

Divergence between the upper plate and trench (Figure 1, case (ii)) can be observed in geometrically complex active margins characterized by strongly oblique convergence, and may represent a local, transient response to the far-field plate motion along suitably oriented orogenic segments [*Malusà et al*., 2011a, their Figure 6d]. In case (ii), when the upper plate moves away from the trench, extension is localized within the weak portion of the upper plate, and reactivates preexisting shear zones in the rear of the accretionary wedge. Exhumation thus occurs on the upper plate side of the subduction system (full red arrow in Figure 1b), bringing (U)HP rocks to the surface from subcrustal depths. In this scenario, turbidites accumulating along the trench axis during exhumation (black star in Figure 1b) are unmetamorphosed, only slightly deformed, and are generally preserved unconformably on top of their basement. Divergence between upper plate and trench may lead to a decrease in slab steepness, because the slab is free to move upward to fill the gap with the diverging upper plate (Figure 1b). Such a shallowing of the slab may provide a suitable mechanism to facilitate exhumation of the overlying (U)HP rocks above the middle crust, where uplifting rocks may become neutrally buoyant [*Ernst et al*., 1997]. The predicted geologic record in this case (Figure 1c, case (ii)) is (U)HP rocks exhumed on the upper plate side of the orogen at the rear of a lower-pressure accretionary wedge, associated with sedimentary sequences attesting to sedimentary basins that were starved of orogenic detritus during (U)HP exhumation. Synexhumation sedimentary successions deposited on the lower plate are unconformably preserved on top of their basement.

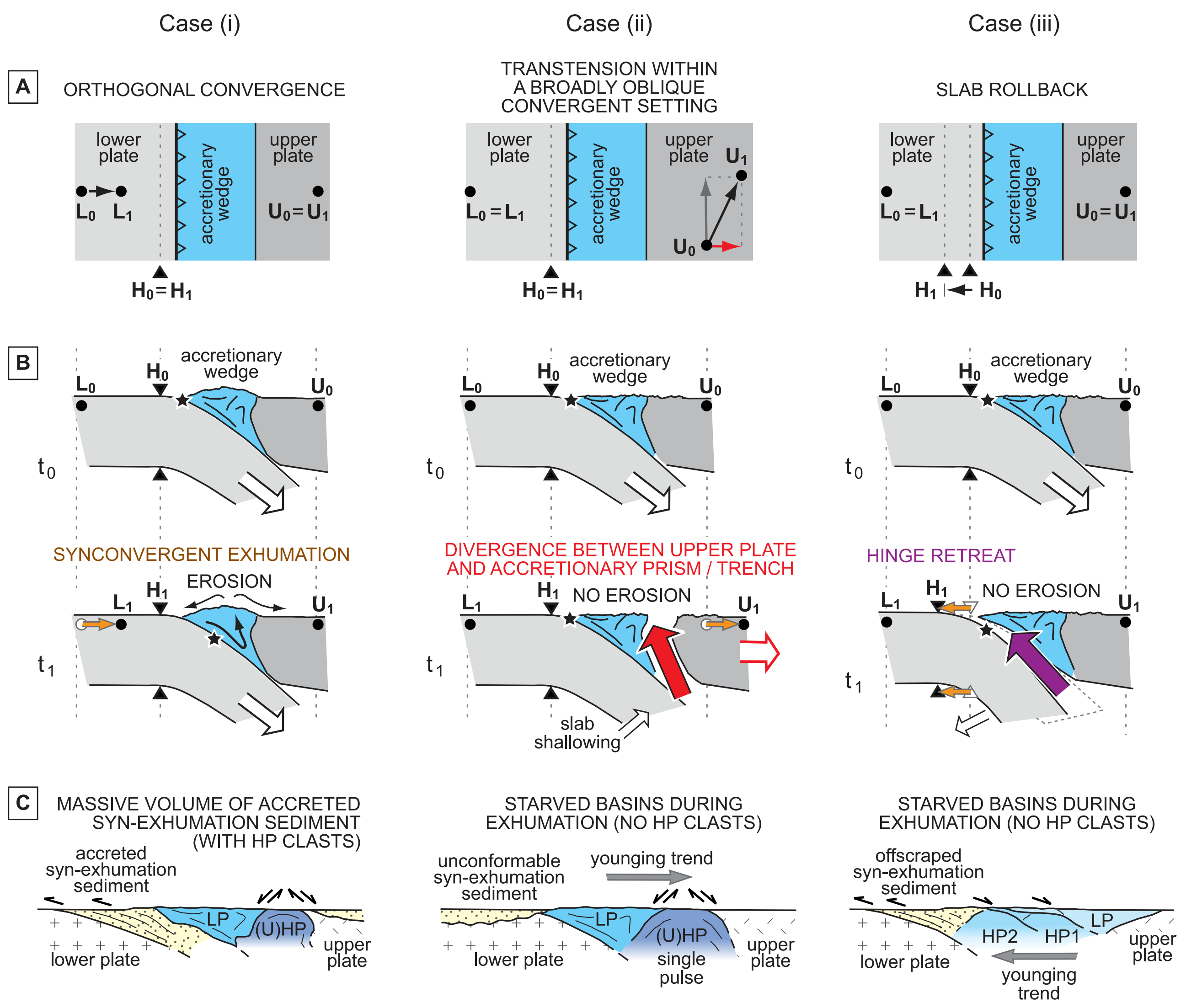

Figure 1. Exhumation mechanisms discussed in this paper: (a) map view and (b) cross sections, and (c) predicted geologic record; black dots indicate fixed points on lower (L) and upper (U) plates; H is the subduction hinge; stars indicate trench turbidites accumulated at time t_0. (left) Case (i)—exhumation during orthogonal convergence between upper and lower plate (i.e., L moves toward the accretionary wedge) [e.g., *Beaumont et al.*, 2001]: massive volumes of synexhumation orogenic detritus (including HP clasts) are accreted at the toe of the wedge and/or underplated (see also Figure 2). (middle) Case (ii)—upper plate motion away from the trench (i.e., U moves away from the accretionary wedge) [e.g., *Malusà et al.*, 2011a]: extension focuses in the rear of the accretionary wedge, (U)HP exhumation occurs on the upper plate side of the orogen (full red arrow); slab shallowing may occur to fill the gap with the diverging upper plate; erosion plays a minor role, trench turbidites (without HP clasts) are unconformably preserved on top of the basement units of the lower plate.(right) Case (iii)—retreat of the subduction hinge (i.e., H moves away from the accretionary wedge) [e.g., *Brun and Faccenna*, 2008]: lower plate and accretionary wedge are decoupled, HP rocks are exhumed on the lower plate side of the orogen (purple arrow); exhumation pulses get progressively younger toward the foreland, slab steepness may decrease as the slab moves away from the upper plate during hinge retreat; erosion plays a minor role, turbidites undetached from the lower plate are subducted. Note that hinge retreat allows subduction also in the case where there is no convergence between the upper and the lower plates.

In contrast, hinge retreat in the lower plate (Figure 1, case (iii)) could be either fostered by a favorable lithosphere-asthenosphere relative motion [e.g., *Doglioni et al.*, 1999], by a change in the buoyancy and rheological structure of the slab [e.g., *Di Giuseppe et al.*, 2009], or by subduction of continental ribbons leading to repeated exhumation pulses each time a distinct ribbon reaches the trench [e.g., *Lister et al.*, 2001; *Brun and Faccenna*, 2008; *Bialas et al.*, 2011]. Slab rollback implies decoupling between the subducting lower plate and the overlying accretionary wedge, and results in the forelandward shift of the subduction zone during progressive accretion on the overriding plate. HP rock exhumation thus occurs on the lower plate side of the accretionary wedge (purple arrow in Figure 1b). Unlike exhumation driven by relative movement of the upper plate away from the trench, several burial/exhumation pulses are generally expected, and the age of the pressure peak assemblages gets younger toward the foreland, from the inner to the external

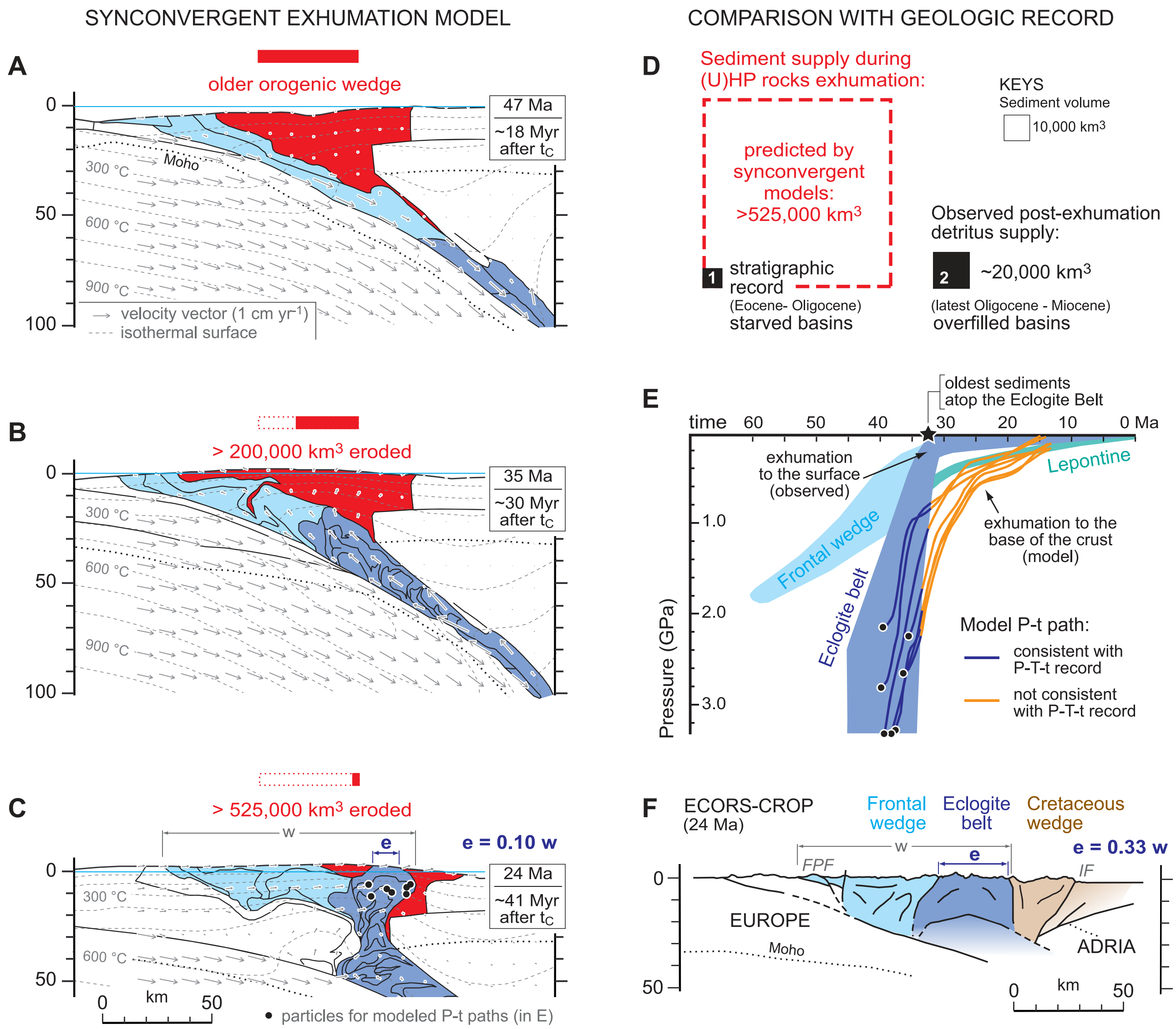

Figure 2. Two-dimensional numerical model of synconvergent exhumation applied to the Western Alps [after *Butler et al.*, 2013] and comparison with geologic record. (a) After continental collision at time $t_c = 65$ Ma, continental crust undergoes (U)HP metamorphism and is detached and stored with previously accreted oceanic material; (b) a plume of buoyant material is inserted into the base of the crust, which is accompanied by extension in the overlying wedge; (c) exhumation takes place in the upper crust in the hanging wall of a retroshear zone. Note the dramatic size reduction of the preexisting orogenic wedge (in red). (d) Comparison with the stratigraphic record: according to the model, >525,000 km^3 detritus would be produced to exhume the Eclogite belt to the surface, which is not comparable with the much lower sediment volume found in the starved Eocene-Oligocene basins (1, in black); (e) pressure-time data for model particles are largely inconsistent with the exhumation paths recorded by the Eclogite belt of the Western Alps [from *Malusà et al.*, 2011a], which was rapidly exhumed directly to the Earth's surface; (f) in spite of the huge amount of detritus required, the size of HP volumes for synconvergent exhumation (e = 0.10 w in Figure 2c) is much smaller than what observed in the Western Alps (e = 0.33 w).

zones of the orogen [e.g., *Rosenbaum and Lister*, 2005; *Lister and Forster*, 2009]. Turbidites accumulating along the trench axis during exhumation are either offscraped, or subducted together with the underlying basement (black star in Figure 1b), whereas a decrease in slab steepness may occur as the slab moves away from the upper plate during hinge retreat [*Brun and Faccenna*, 2008]. The predicted geologic record in this case (Figure 1c, case (iii)) is HP rocks exhumed in the frontal part of the accretionary wedge and showing a younging trend toward the foreland, associated with sedimentary sequences attesting to minor orogenic erosion during HP rock exhumation. Synexhumation sedimentary sequences are generally offscraped from their basement.

We use the geologic record preserved in the western Mediterranean to illustrate the contrasting records of cases (ii) and (iii), as both mechanisms leading to boundary divergence within the subduction zone have occurred along the Cenozoic Adria-Europe plate boundary. The case of divergence between the upper plate and trench is illustrated using examples from the Western Alps, the case of exhumation during slab rollback is illustrated by examples from the Apennines.

3. The Western Mediterranean Study Area

The western Mediterranean area (Figure 3, top left) is the result of a complex Meso-Cenozoic evolution along the boundary between the Eurasian and African plates [e.g., *Dewey et al*., 1989; *Jolivet and Faccenna*, 2000; *Rosenbaum et al*., 2002; *Giacomuzzi et al*., 2011; *Carminati et al*., 2012]. It includes Cenozoic orogenic belts (Alps, Apennines, Betics, and Pyrenées) related to different, possibly interacting subduction zones [*Jolivet et al*., 2003; *Vignaroli et al*., 2008a; *Malusà et al*., 2011a], and large Neogene backarc basins (Ligurian-Provençal and Tyrrhenian) that partly mask the original relationships between these belts. Remnants of the Mesozoic Tethyan crust are possibly preserved in the Ionian Sea.

Within the Alps-Apennines system, Cenozoic HP units with different paleogeographic positions, metamorphic age, and peak P-T conditions are variably exposed not only in the Alps-Apennines mountain range, but also in Corsica and in other minor Tyrrhenian islands (i.e., the Tuscan archipelago), and at various locations on the Tyrrhenian seafloor (Figures 3 and 4). In the Western Alps (Figure 3a), major continental and oceanic (U)HP units have been described and mapped in the field since the beginning of the twentieth century [e.g., *Franchi*, 1902; *Compagnoni and Maffeo*, 1973; *Dal Piaz et al*., 1983, 2010; *Elter*, 1987; *Polino et al*., 2002, 2010; *Capponi et al*., 2008]. To the south, HP rocks have been mapped in the Tuscan metamorphic complexes of the Northern Apennines (Figure 4) [e.g., *Carmignani and Kligfield*, 1990; *Jolivet et al*., 1998; *Balestrieri et al*., 2011], and in the Calabria-Peloritani arc [e.g., *Rossetti et al*., 2001a; *Iannace et al*., 2007]. The major plates involved in these orogenic segments are the European plate to the northwest, and the Adriatic microplate to the southeast. The Adriatic microplate possibly represents a promontory of the larger African plate located farther to the south [*Channell et al*., 1979].

Crustal sections across the Alps-Apennines system show that Adria represents the upper plate of the subduction system along the northern segments of the orogen, i.e., in the central and Western Alps (W-W′ and X-X′ in Figure 3), but represents the lower plate along the southern segments, e.g., in the Northern Apennines and Calabria (Z-Z′ and K-K′ in Figure 3). Additional constraints for slab configuration are provided by *P* wave tomography [*Piromallo and Morelli*, 2003]: the high-velocity anomaly corresponding to the European slab can be traced beneath the Western Alps down to ~300 km depth [*Piromallo and Faccenna*, 2004], whereas the Adriatic slab can be traced, to the south, for ~700 km beneath the Northern Apennines and for ~1300 km beneath Calabria [*Faccenna et al*., 2004].

Because (U)HP rocks have been exhumed and are now found at various sites along the orogen, and the same plate (Adria) acted as upper plate to the north and as lower plate to the south, the Alps-Apennines system represents the ideal site to compare the role exerted by upper and lower plates during exhumation of (U)HP rocks. After an overview of the Meso-Cenozoic evolution of the Adria-Europe plate boundary (section 4), (U)HP rock exhumation will be analyzed in detail along three different transects, i.e., in the Western Alps (section 5), Calabria (section 6), and Corsica-Northern Apennines (section 7).

4. Evolution of the Adria-Europe Plate Boundary

The Meso-Cenozoic evolution of the Adria-Europe plate boundary is summarized in the palinspastic reconstructions illustrated in Figure 5. These maps, based on *Malusà et al*. [2015], encompass the first-order geologic constraints available for the Adria-Europe plate boundary zone, including the relative Adria-Europe plate motion (purple arrows), the trend of the paleomargins (thick dashed lines), and the orientation of the Alpine and Apenninic trenches. The trend of the Adriatic and European passive margins is constrained by stratigraphic evidence in the South Alpine successions [*Winterer and Bosellini*, 1981; *Bertotti et al*., 1993; *Fantoni and Franciosi*, 2010], and by low-temperature thermochronologic data in Corsica-Sardinia

[*Malusà et al.*, 2015]. The paleotrench orientation during subduction in the central and Western Alps is obtained by retrodeformation in the foreland and retroforeland areas [e.g., *Schönborn*, 1992; *Sinclair*, 1997; *Lickorish and Ford*, 1998]. Due to the minor shortening documented along the Western Alps segment since

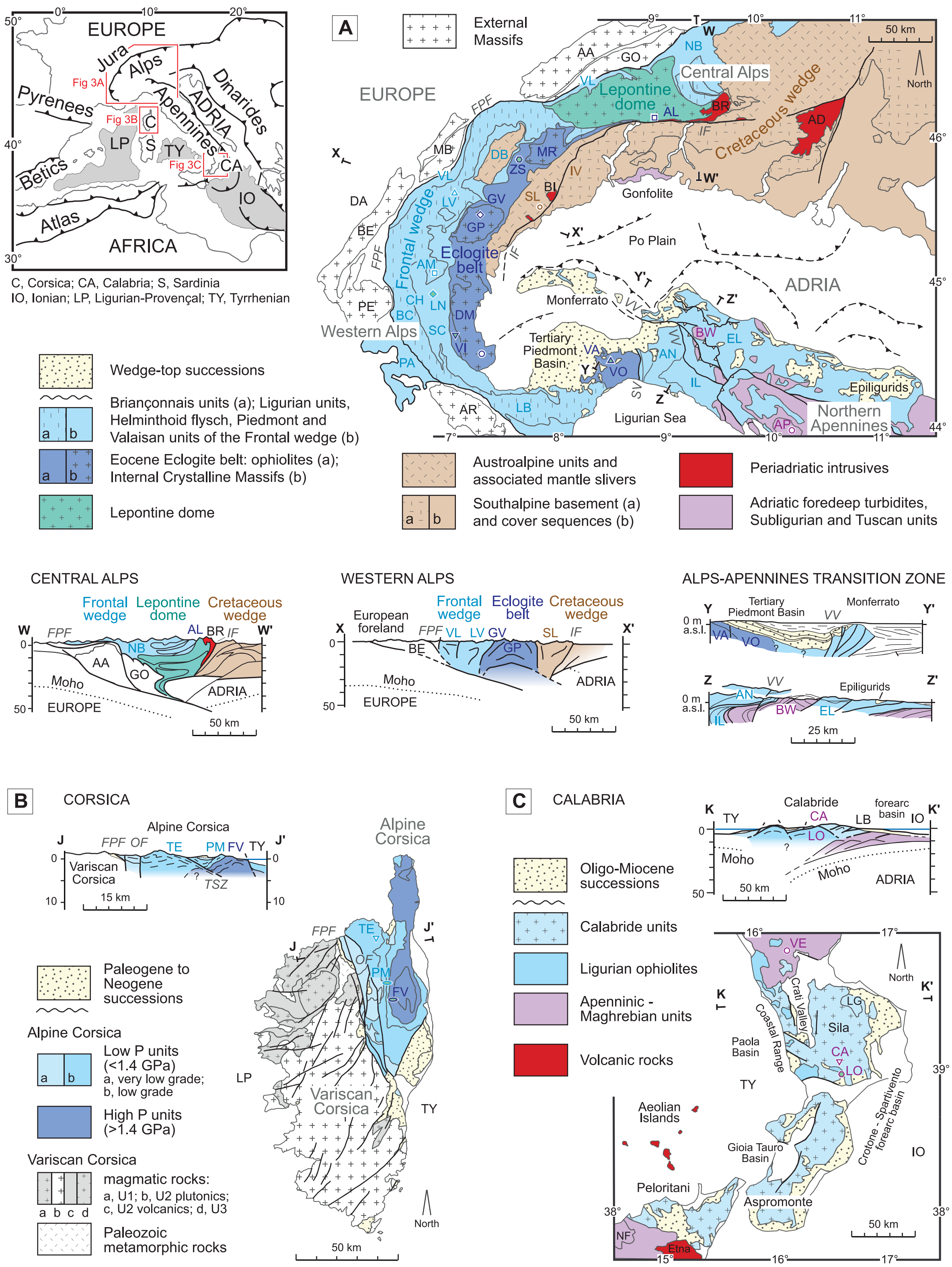

Figure 3.

the Oligocene (on the order of 10^1 km) [*Malusà et al*., 2009, and references therein], the resulting paleotrench configuration shows a major right-angle bend between the central and the Western Alps, which mirrors the configuration inherited from the Adriatic passive margin that is largely preserved south of the Alps [e.g., *Fantoni and Franciosi*, 2010, their Figure 3]. Farther south, along the future Provençal margin, the paleotrench orientation is constrained by paleomagnetic data and by the morphological fit of the Ligurian-Provençal basin margins [e.g., *Séranne*, 1999; *Gattacceca et al*., 2007; *Jolivet et al*., 2015]. These data point to a NE-SW trend of that segment of the paleotrench before the opening of the Neogene backarc basins. The resulting paleotrench configuration, shown in Figures 5c and 5d, is consistent with the present-day trace of the European slab imaged by seismic tomography at 150 km depth (Figure 6, top left) [*Malusà et al*., 2011a].

The rotation poles of *Dewey et al*. [1989] provide an estimate of the Adria-Europe relative motion during the last 100 Ma, leading to solutions that are consistent with those provided by alternative velocity models [e.g., *Savostin et al*., 1986; *Jolivet and Faccenna*, 2000; *Rosenbaum et al*., 2002; *Capitanio and Goes*, 2006] (a detailed discussion on uncertainties in kinematic parameters can be found in *Jolivet and Faccenna* [2000]). In Figure 5, we considered coherent motion of Adria with Africa during most of the Meso-Cenozoic, as indicated by paleogeographic evidence and paleomagnetic data [*Channell et al*., 1979; *Van der Voo*, 1993; *Muttoni et al*., 2001]. First-order consequences of these palinspastic reconstructions include: (i) the obliquity of Adria motion relative to the paleotrench and (ii) the obliquity of the Western Alps paleotrench relative to the European paleomargin of the Tethys.

The slab lengths observed in tomographic sections [*Piromallo and Morelli*, 2003; *Faccenna et al*., 2004], and the age and location of subduction-related magmatism [*Lustrino et al*., 2009], provide independent constraints to validate these palinspastic restorations. Slab lengths observed in tomographic sections are in fact fully consistent with those independently predicted by palinspastic reconstructions taking into account rollback, convergence, and lateral slab translation (Figure 6). Additionally, the first arrival of the Adriatic slab at ~100 km depth during subduction matches with the onset of orogenic magmatism in Sardinia (Calabona locality) [*Lustrino et al*., 2009], in line with current models of magma generation.

4.1. Opening and Closure of the Alpine Tethys

During the Alpine orogeny, subduction along the Adria-Europe plate boundary led to the demise of the Mesozoic Tethyan Ocean, and involved the adjoining passive margins [*Bernoulli et al*., 1979; *Vialon*, 1990; *Handy et al*., 2010]. Today, a nearly complete section of the former Adriatic margin can be reconstructed by examination of the Cretaceous wedge of the central Alps [*Manatschal and Nievergelt*, 1997]. There, units derived from the proximal margin (upper Austroalpine nappes), distal margin (lower Austroalpine and Err nappes), and ocean-continent transition (Platta and Malenco nappes) were first telescoped, and then extended E-W in the Late Cretaceous [*Froitzheim et al*., 1994; *Manatschal et al*., 2003; *Manatschal*, 2004]. Another complete section of the former Adriatic margin, and originally located farther south, can be observed south of the Insubric Fault (South Alpine domain, SO in Figure 5a), where the Mesozoic rift structure, sampled in south-vergent nonmetamorphic thrust sheets, shows a NNE-SSW trend [*Winterer and Bosellini*, 1981; *Bertotti et al*., 1993; *Schumacher et al*., 1997].

The proximal and distal portions of the paleo-European margin are preserved in the Dauphinois (DA in Figure 5a) and in the Briançonnais (BC in Figure 5a) successions of the Western Alps [*Lemoine et al*., 1986; *Jaillard*, 1989], where they were delaminated and accreted within basement and sedimentary cover nappes. The Valaisan units (VL in Figure 3a), exposed between the Dauphinois and Briançonnais successions, are sometimes ascribed to an independent oceanic domain, referred to as the Valaisan ocean, but may simply indicate that the Tethyan ocean was not completely subducted and still existed to the NE until the late

Figure 3. (top left) Tectonic sketch map of the western Mediterranean, geologic maps of the study areas, and representative cross sections. (a) Central and Western Alps, including the transition zone with the Northern Apennines (main tectonic domains according to *Malusà et al*. [2011a] and *Malusà and Balestrieri* [2012]). Cross sections: W-W′, based on crustal seismic data along the EGT NRP20 traverse, modified after *Pfiffner et al*. [2002]; X-X′, based on crustal seismic data along the ECORS-CROP traverse [*Polino et al*., 1990], modified after *Malusà et al*. [2011a]; Y-Y′, based on seismic data in *Rossi et al*. [2009b], modified after *Malusà and Balestrieri* [2012]; Z-Z′, modified after *Cerrina Feroni et al*. [2004]. (b) Corsica (simplified after *Carmignani et al*. [2000]). Alpine P-T conditions according to *Lahondère* [1996], *Jolivet et al*. [1998], and *Vitale Brovarone et al*. [2013]; Variscan basement according to *Cocherie et al*. [2005]. Cross-section J-J′ based on *Daniel et al*. [1996], modified according to original field data. (c) Calabria (map after *Faccenna et al*. [2004]). Cross-section K-K′ based on *Rossetti et al*. [2001a, 2004], *Piana Agostinetti and Amato* [2009], *Minelli and Faccenna* [2010], and *Vignaroli et al*. [2012]. Acronyms: AL, Alpe Arami; AA, Aar; AD, Adamello; AM, Ambin; AN, Antola; AR, Argentera; BC, Briançonnais; BE, Belledonne; BI, Biella; BR, Bregaglia-Bergell; BW, Bobbio window; CA, Castagna; CH, Chenaillet; DA, Dauphinois; DB, Dent Blanche; DM, Dora-Maira; EL, External Ligurids; FV, Farinole-Volpajola; GO, Gotthard; GP, Gran Paradiso; GV, Grivola; IL, Internal Ligurids; IV, Ivrea-Verbano; LB, Ligurian Briançonnais; LG, Longobucco; LN, Lago Nero; LO, Gimigliano lower Ophiolites; LP, Ligurian-Provençal; LV, Leverogne; MB, Mont Blanc; MR, Monte Rosa; NB, North Penninic calcschists; NF, Numidian Flysch; PA, Parpaillon; PE, Pelvoux; PM, Pigno-Morosaglia; SC, Queyras calcschists; SL, Sesia-Lanzo; TE, Tenda; TY, Tyrrhenian; VA, Valosio; VE, Lungro-Verbicaro; VI, Viso; VL, Valaisan; VO, Voltri; ZS, Zermatt-Saas. Major faults (italics): FPF, Frontal Pennine; IF, Insubric; OF, Ostriconi; SV, Sestri-Voltaggio; TSZ, Tenda shear zone; VV, Villalvernia-Varzi-Ottone. Open symbols indicate location of samples shown in Figures 7–10 (green fillings for ophiolites).

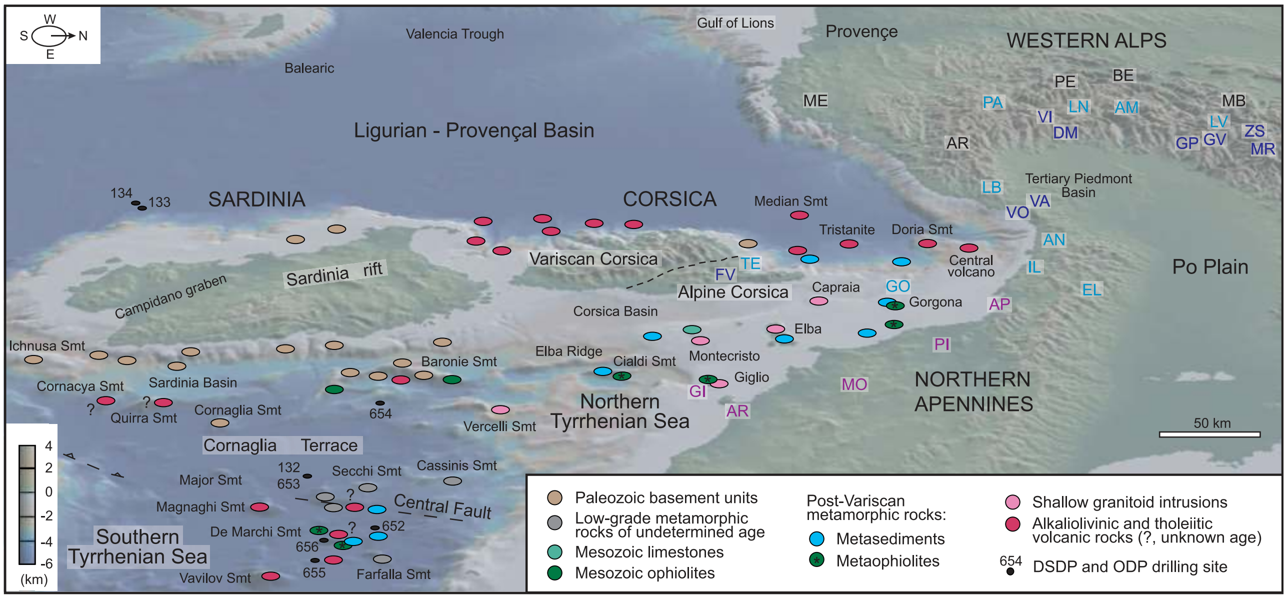

Figure 4. Digital topographic-bathymetric model of the Western Alps, Northern Apennines, Corsica-Sardinia, and adjoining back-arc basins (after http://www.geomapapp.org and *Ryan et al.* [2009]) (looking west, 3/1 vertical exaggeration). Circles indicate rocks exposed in minor islands or found in drillings in the Tyrrhenian and Ligurian-Provençal basins (compiled after *Colantoni et al.* [1981], *Sartori* [1986], *Schreider et al.* [1986], *Bigi et al.* [1991, 1992], *Mauffret et al.* [1999], *Sartori et al.* [2004], and *Réhault et al.* [2012]). Note the contrasting physiography and basement lithology in the northern and southern Tyrrhenian and the drastic change in basement lithology across the central Fault. Acronyms: Eclogite belt (dark blue)—DM, Dora-Maira; FV, Farinole-Volpajola; GP, Gran Paradiso; GV, Grivola; MR, Monte Rosa; VA, Valosio; VI, Viso; VO, Voltri; ZS, Zermatt-Saas. Frontal wedge and Ligurian units (light blue)—AM, Ambin; AN, Antola; EL, External Ligurids; GO, Gorgona; IL, Internal Ligurids; LB, Ligurian Briançonnais; LN, Lago Nero; LV, Leverogne; PA, Parpaillon; TE, Tenda. Tuscan metamorphic units (purple)—AP, Apuane; AR, Argentario; GI, Giglio; MO, Monticiano Roccastrada; PI, Monti Pisani. European basement (black)—AR, Argentera; BE, Belledonne; MB, Mont Blanc; ME, Maures Esterel; PE, Pelvoux.

Eocene (Figures 5a and 5c). The European distal margin is also well preserved in Sardinia [*Fourcade et al.*, 1993; *Costamagna et al.*, 2007; *Jadoul et al.*, 2010], where it is not involved in subsequent accretion. Thermochronologic data from Corsica-Sardinia indicate that the European margin had an original ENE-WSW strike [*Malusà et al.*, 2015], parallel to the major Variscan faults exposed on the mainland (e.g., Cévennes Fault) [*Arthaud and Seguret*, 1981; *Vialon*, 1990; *Guillot et al.*, 2009b].

The first evidence of strong, differential subsidence associated with faulting along the future margins of the Tethys are recorded in the Alps from the Late Triassic, and were more apparent on the Adriatic side [*Bertotti et al.*, 1993; *Berra*, 1995; *Manatschal*, 2004]. Rifting was initially distributed, then extension became localized along a few major faults, to be eventually concentrated within the area of future lithospheric breakup. Detachment faulting led to the exhumation of subcontinental mantle and to the emplacement and exhumation of gabbros on the seafloor [*Lagabrielle and Lemoine*, 1997]. The age of breakup is constrained by the crystallization ages of gabbros and trondhjemites (158–169 Ma) [*Ohnenstetter et al.*, 1981; *Rossi et al.*, 2002; *Li et al.*, 2013], by the biostratigraphic ages of overlying radiolarites (upper Bathonian-lower Callovian) [*Chiari et al.*, 2000; *Danelian et al.*, 2008], and by rapid cooling recorded by fission track data during breakup [*Malusà et al.*, 2015]. In the distal European margin, karst features in Triassic-Lower Jurassic carbonates are filled by Middle Jurassic sediments, attesting to a change from initial subsidence and block tilting to uplift during a later stage of the rifting [*Lemoine et al.*, 1986]. At the same time, the conjugate Adriatic margin was subsiding beneath the calcite compensation depth as indicated by deposition of radiolarian cherts [*Winterer and Bosellini*, 1981]. For this reason, a simple-shear model for the Tethyan rifting, including a west-dipping detachment fault, was originally proposed by *Lemoine et al.* [1987], and may also explain the exhumation of lower crust on the Adriatic side of the Tethys as compared to the widespread exposure of upper crustal rocks on the European side.

Adria started moving NE-ward relative to Europe in Cretaceous times [*Dewey et al.*, 1989], leading to the accretion of extensional allochthons consisting of Adriatic crust (Austroalpine units) to form the Cretaceous wedge (Figure 5a). Along the central-Eastern Alps trench, the accretion of the Austroalpine units was followed by subduction of Tethyan crust beneath the Adriatic plate [*Zanchetta et al.*, 2012]. Farther south, motion of Adria was initially near-parallel to the northern Tethyan margin (Figure 5a), which is largely preserved in Sardinia north of

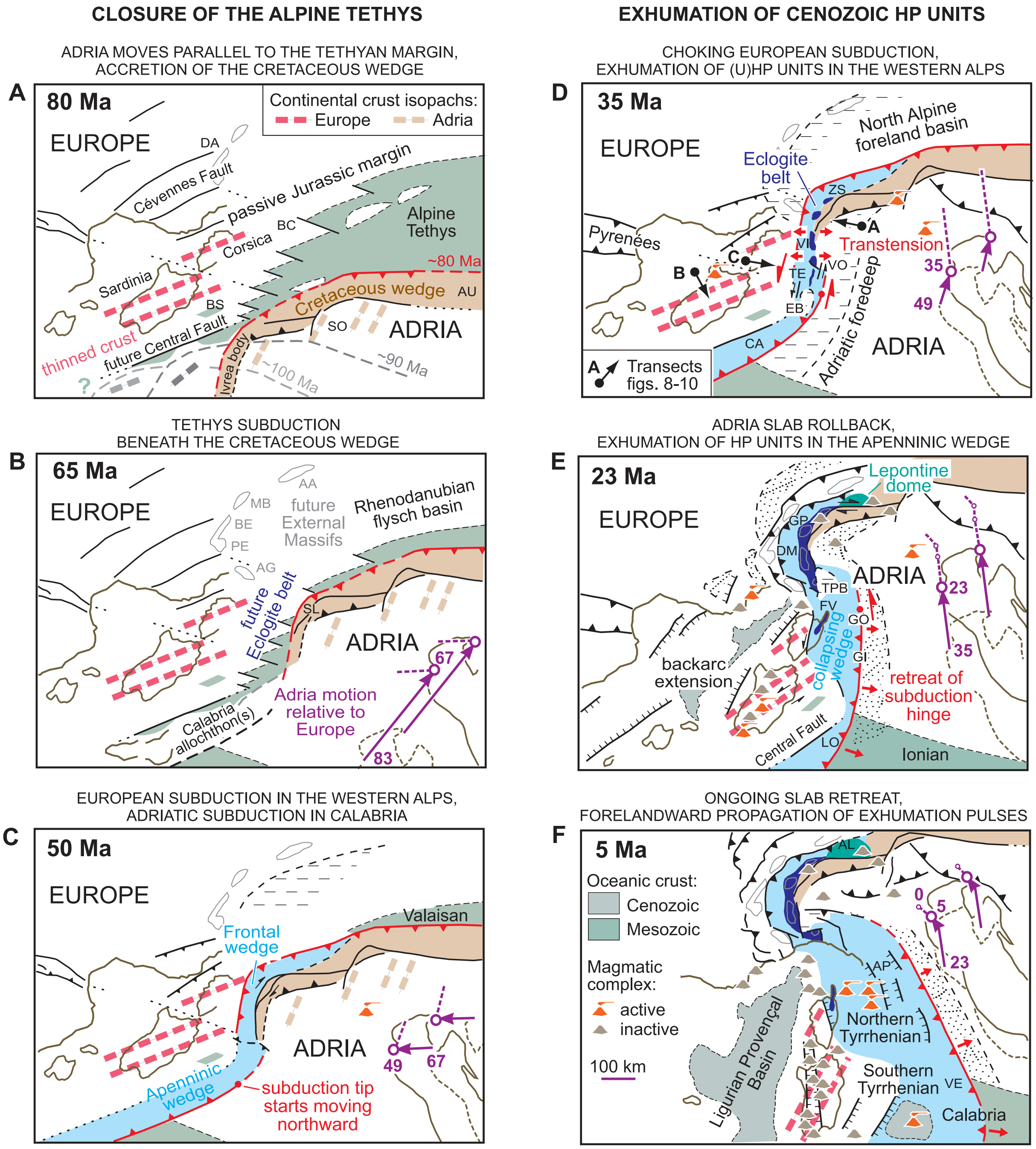

Figure 5. Evolution of the Alps-Apennines system since the Cretaceous (shape of Adria promontory and enclosed Cretaceous wedge from *Malusà et al.* [2011a]; Adria trajectories relative to Europe from *Dewey et al.* [1989] and *Jolivet and Faccenna* [2000]; European Tethyan margin and migrating tip of Adriatic subduction from *Malusà et al.* [2015]). Active subduction zones are marked in red. (b) In mid-Cretaceous times, Sardinia faces the South Alpine domain (SO); the European and Adriatic continental margins are parallel to the major Variscan faults on the mainland (e.g., Cévennes Fault); between 100 and 80 Ma, Adria rotates counterclockwise and moves near-parallel to the Tethyan passive margin, which is preserved north of the future central Fault. (b) In the latest Cretaceous, the Alpine Tethys is almost closed by Alpine subduction (the future External Massifs are shown in grey for reference); accretion of Austro-alpine units (AU) in the Cretaceous wedge, including the Sesia-Lanzo (SL), is completed; the inherited tectonic configuration south of the central Fault includes slivers of lower crust now exposed in Calabria. (c) E-W Adria-Europe convergence (67–49 Ma) is accommodated along the Corsica transect by eastward subduction propagating from the Eastern Alps, and along the Sardinia transect by westward subduction possibly propagating from the Betics. (d) Choking of Alpine subduction and localized extension in the Alpine trench in the late Eocene triggers extremely fast exhumation of the Eclogite belt [*Malusà et al.*, 2011a]; Adria subduction is still active to the south, the Adriatic slab moves northward beneath Sardinia. (e) The Adriatic slab shifts farther north beneath the Alpine wedge of Corsica; the onset of slab rollback induces extension in the back-arc region; Adriatic foredeep turbidites fed from the Lepontine dome are progressively accreted within the Apenninic wedge. (f) The Corsica-Sardinia block has completed its counterclockwise rotation; west of the central Fault, the inheritance of Tethyan rifting is still largely preserved. Acronyms: AA, Aar; AL, Alpe Arami; AP, Apuane; AR, Argentera; AU, Austroalpine; BE, Belledonne; BS, Baronie Smt; CA, Castagna; DM, Dora-Maira; EB, Epiligurian basins; FV, Farinole-Volpajola; GI, Giglio; GO, Gorgona; GP, Gran Paradiso; LO, Gimigliano lower ophiolites; VE, Lungro-Verbicaro; MB, Mont Blanc; PE, Pelvoux; SL, Sesia-Lanzo; SO, South Alpine; TE, Tenda; TPB, Tertiary Piedmont Basin; VI, Viso; VO, Voltri ZS, Zermatt-Saas.

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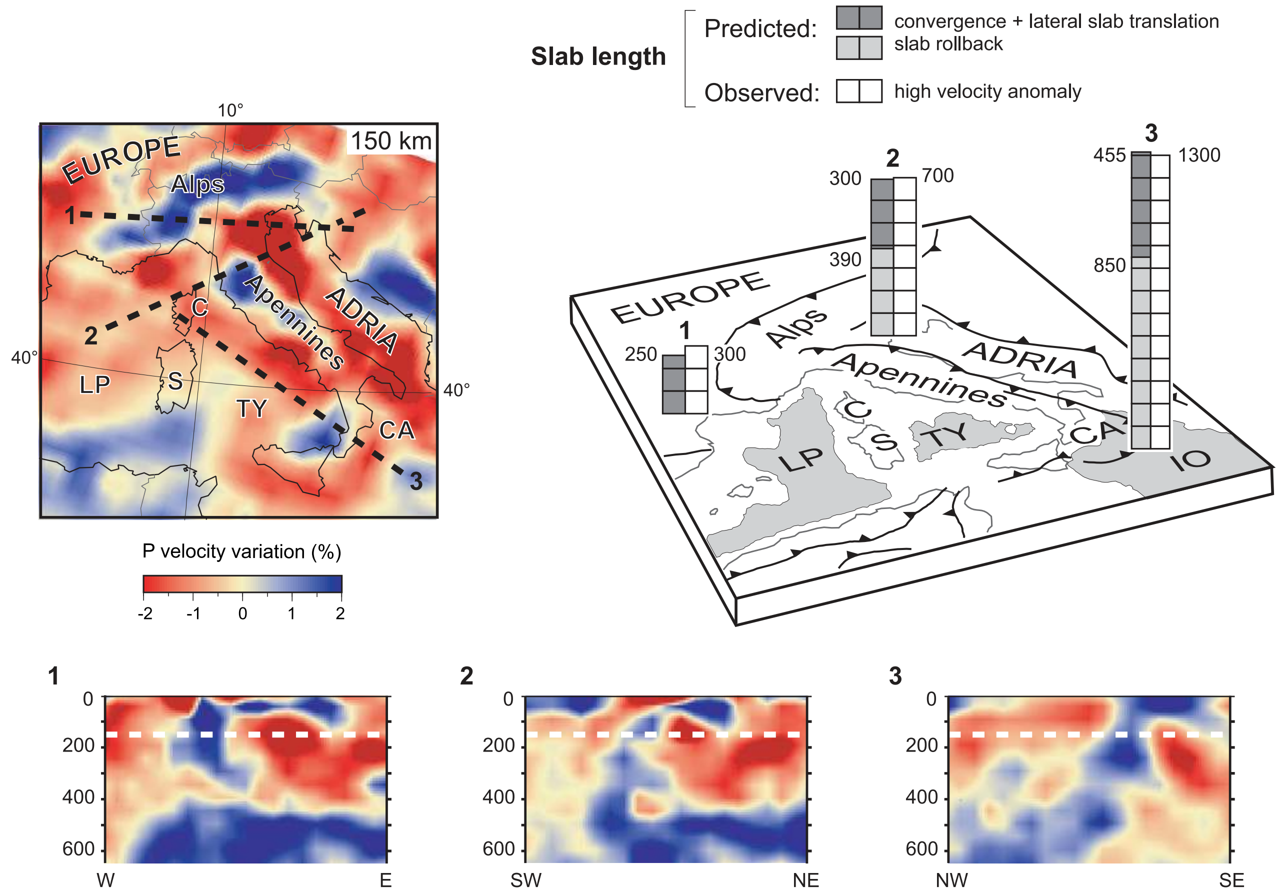

Figure 6. Validation of the Alps-Apennines evolution model based on tomographic data. Prediction of slab length taking into account rollback, convergence and lateral slab translation according to the model of Figure 5, is fully consistent with the high-velocity anomaly observed in tomographic sections across the Western Alps (1), Corsica-Northern Apennines (2), and Calabria (3) (tomographic data after *Piromallo and Morelli* [2003] and *Piromallo and Faccenna* [2004]).

the future central Fault [*Malusà et al.*, 2015] (Figure 5b). The tectonic configuration south of the central Fault was more complex due to the translation of the Cretaceous wedge, and possibly incorporated slivers of lower continental crust now exposed in Calabria. Tethys closure by Alpine subduction was almost complete by the latest Cretaceous (Figure 5b), and remnants of Tethyan crust are now accreted within the orogenic wedge. Exhumed subcontinental mantle not involved within the orogenic wedge is possibly preserved offshore eastern Sardinia [*Malusà et al.*, 2015], and was possibly sampled in the Baronie seamount (BS in Figure 5) [*Schreider et al.*, 1986; *Yastrebov et al.*, 1988]. The $>$4 km deep Ionian seafloor (Figure 3) may represent a major oceanic relict of Mesozoic age, but the nature of this remnant abyssal plain is still disputed [e.g., *Biju-Duval et al.*, 1977; *Finetti*, 1982; *Boccaletti et al.*, 1984; *Nicolich et al.*, 2000].

4.2. Relationships Between Alpine and Apenninic Subduction

In the western Mediterranean, the original southward extension of the Alpine orogenic wedge during the Paleogene and the transition in space and time between the opposite-dipping European (Alpine) and Adriatic (Apenninic) subduction zones have long been debated [*Gueguen et al.*, 1997; *Jolivet et al.*, 1998; *Faccenna et al.*, 2001a; *Molli and Malavieille*, 2011; *Argnani*, 2012; *Carminati et al.*, 2012; *Turco et al.*, 2012]. End-member hypotheses envisage either the occurrence of two coeval opposite-dipping subduction zones (the Alpine one to the north and the Apenninic one to the south—the so-called "ancient-Apennines" hypothesis) [e.g., *Principi and Treves*, 1984; *Rossetti et al.*, 2001a] or the occurrence of a Cretaceous-to-Eocene Alpine subduction zone developed across the whole western Mediterranean, later replaced by a westward Apenninic subduction developed at the rear of the Alpine wedge since the Oligocene (the so-called "young-Apennines" hypothesis) [e.g., *Boccaletti et al.*, 1971; *Doglioni et al.*, 1998; *Handy et al.*, 2010]. Fundamental clues to solve this debate are provided by fission-track and (U-Th)/He data from Corsica-Sardinia [*Danišík et al*., 2007, 2012; *Malusà et al*., 2015], which show that the European distal margin of the Tethys, exposed in Sardinia, still preserves the low-temperature thermochronologic history acquired during Tethyan rifting. This finding precludes any subduction of European continental crust south of Corsica since the Mesozoic.

A viable Paleocene-early Eocene scenario for the Adria-Europe plate boundary thus includes an eastward (Alpine) subduction propagating from the central-Eastern Alps, that was active along the Western Alps and Corsica transect, and a coeval northwestward (Apenninic) subduction that was active along the Sardinia transect. The E-W Adria-Europe convergence predicted by plate-motion constraints (Figure 5c) was thus accommodated by opposite-dipping subduction zones, juxtaposed along the eastern continuation of the future Pyrenées. In the middle-late Eocene, Alpine subduction was choked by the arrival of thick continental crust at the trench, while Adria started moving NNE-ward (Figure 5d). Localized extension within the choked Alpine subduction channel ($\sim$30 km extension according to *Malusà et al*. [2011a]) triggered the extremely rapid exhumation of the Eclogite belt in the late Eocene. This occurred while the Adriatic slab started its northward motion, obliquely subducting beneath Corsica, and reaching the remnants of the Alpine wedge in Oligocene times (Figure 5e) [*Malusà et al*., 2015].

4.3. Opening of the Neogene Backarc Basins

By the end of the Oligocene, when the Adriatic plate was still obliquely converging with northward motion relative to Europe (Figure 5e), the Adriatic trench began retreating toward the east [*Malinverno and Ryan*, 1986; *Jolivet and Faccenna*, 2000]. Intermittent trench retreat produced back-arc extension at an average rate of a few centimeters per year, leading to the opening of the Ligurian-Provençal basin [*Jolivet et al*., 2015] and associated 45° counterclockwise rotation of the Corsica-Sardinia block, constrained to have chiefly occurred between 20.5 and 15 Ma by paleomagnetic data [*Gattacceca et al*., 2007]. Meanwhile, the Adriatic foredeep turbidites supplied from the exhuming central Alps were progressively accreted within the Apenninic wedge [*Ricci Lucchi*, 1990; *Garzanti and Malusà*, 2008] (Figure 5e). During early Miocene rifting, the crust beneath the Ligurian-Provençal basin, now floored by oceanic crust [*Mauffret et al*., 1995; *Rollet et al*., 2002], was thinned from $\sim$25 to $\sim$5 km [*Bois*, 1993; *Chamot-Rooke et al*., 1999]. Seafloor spreading was broadly coeval with the climax of orogenic volcanism in Sardinia [*Lustrino et al*., 2009], but magmatism is also documented north of Corsica and along the northern offshore continuation of the Sardinia rift [*Réhault et al*., 2012] (Figure 4).

In the late Miocene, extension east of Corsica-Sardinia led to the opening of the Tyrrhenian basin (Figure 5f), reactivating preexisting structures inherited from Alpine convergence offshore Corsica, and those inherited from Tethyan rifting offshore Sardinia. The Tyrrhenian basin shows contrasting features in its northern and southern parts in terms of bathymetry, basement lithology, and Moho depth (Figure 4). The northern Tyrrhenian Sea is relatively shallow and has a 22–25 km deep Moho [*Mauffret et al*., 1999]. The basement includes post-Variscan metasediments, metaophiolites, and limestones that are ascribed to a Cenozoic accretionary wedge. These rocks are unconformably overlain by Eocene to Recent deposits, exceeding 8.5 km thickness in the Oligocene-early Miocene Corsica basin, and are intruded by upper Miocene-lower Pliocene granitoids [*Colantoni et al*., 1981; *Mascle and Rehault*, 1990; *Serri et al*., 1993; *Cornamusini et al*., 2002; *Pascucci*, 2002].

The southern Tyrrhenian Sea is much deeper (Figure 4), and shows highly asymmetric conjugate margins, $\sim$250 km wide on the Sardinian side, $\sim$120 km wide on the Southern Apennines-Calabria side [*Kastens et al*., 1988; *Mascle and Rehault*, 1990]. On the Sardinian margin, a wide and rather flat area known as the Cornaglia Terrace is bounded to the east by the NNE-trending scarps of the central Fault [*Selli and Fabbri*, 1971], whereas the lower part of the margin includes Plio-Quaternary oceanic areas and the Vavilov and Marsili volcanoes [*Savelli and Schreider*, 1991; *Sartori et al*., 2004; *Nicolosi et al*., 2006]. Thick Messinian evaporites are found on the Cornaglia Terrace, which is identified as a major Messinian depocenter, but these units are missing farther to the east [*Kastens et al*., 1988]. Southern Tyrrhenian basement lithologies include widespread alkali olivine and tholeiitic volcanic rocks, and change markedly across the central Fault (Figure 4): Paleozoic continental units are exclusively found to the west of the fault, whereas the acoustic basement east of the fault includes metasediments and metaophiolites piled up within a Cenozoic accretionary wedge [*Sartori*, 1986; *Sartori et al*., 2001].

The retreat of the Adriatic subduction zone during the Neogene was accompanied by its progressive fragmentation [*Faccenna et al*., 2005]. The relict of this once larger subduction zone is presently limited to a quite narrow (<200 km), deep (>400 km), and steep (70°) NW-dipping Wadati-Benioff zone in the southern Tyrrhenian basin offshore Calabria [*Selvaggi and Chiarabba*, 1995; *Faccenna et al*., 2001b, 2003], and shows no direct linkage with the Southern Apennines slab to the north [*Chiarabba et al*., 2008]. Although the subducted slab beneath Calabria is seismically active down to a depth of 450 km, trench retreat has probably ceased, as indicated by geodetic and paleomagnetic data [*Hollenstein et al*., 2003; *D'Agostino and Selvaggi*, 2004; *Mattei et al*., 2007; *Minelli and Faccenna*, 2010].

5. Exhumation Triggered by Motion of the Upper Plate: The Western Alps

5.1. Tectonic Setting

The European Alps mark the Adria-Europe plate-boundary zone across continental Europe, and are part of a ~250 km wide deformation zone that extends from the Po Plain to the Jura mountains (see the tectonic sketch map in Figure 3). Cenozoic metamorphic units are exposed in the axial part of the belt, between the Insubric Fault and the Frontal Pennine Fault (IF and FPF respectively on Figure 3a) [*Polino et al*., 1990; *Schmid and Kissling*, 2000] and were built within the framework of European (Alpine) subduction, as shown in deep seismic and tomographic profiles (Figures 3a and 6). Because of its obliquity relative to Adria motion, and also to the trend of the European passive margin (Figure 5), the central-eastern and the western segments of the orogen are quite dissimilar. A markedly variable structure is therefore observed along strike, both in map view and in cross sections (Figure 3a).

5.1.1. The Central Alps Segment

The orogenic segment exposed in the central and Eastern Alps chiefly comprises a doubly vergent precollisional orogenic wedge, referred to as the Cretaceous wedge in Figure 3a, and consisting of Adriatic crust accreted against the upper plate (Adria) during the early stages of the Alpine orogeny [*Thöni et al*., 2008; *Zanchetta et al*., 2012]. This wedge, including the Austroalpine units and the South Alpine basement and cover sequences described in the classical Alpine literature [*Frey et al*., 1999], forms a klippe on top of the Cenozoic metamorphic units, and is intruded by Cenozoic magmatic rocks (Periadriatic intrusives) [*von Blanckenburg et al*., 1998; *Rosenberg*, 2004]. The underlying metamorphic units record Paleogene subduction and exhumation of oceanic (Tethyan) and attenuated European continental-margin crust. The HP gneisses exposed in the Lepontine dome represent the deepest levels of the postcollisional nappe stack in this segment of the orogen [*Argand*, 1911]. They are pervasively retrogressed under amphibolite-facies conditions, and are overlain by lower-grade Briançonnais units (Tambò, Suretta) and North Penninic calcschists (section W-W'). Along the central Alps transect, the Adriatic lower crust and the underlying lithospheric mantle act as a rigid indentor beneath the axial belt, and major thrust-sheets are mapped also to the north of the Frontal Pennine Fault.

5.1.2. The Western Alps Segment

In the western segment of the orogen, the Cretaceous wedge is only locally preserved (e.g., Sesia-Lanzo unit), and a 20–25 km wide belt of Eocene eclogite units is exposed adjacent to the Adriatic plate, at the rear of a Cenozoic double-vergence accretionary wedge (section X-X' and Figure 7a). The Eclogite belt of the Western Alps [*Malusà et al*., 2011a] extends from the Lepontine dome in the north, to the Sestri-Voltaggio Fault in the south (Figure 3a). It consists of large coherent units of eclogitized European continental crust, forming tectonic domes also referred to as Internal Crystalline Massifs (Monte Rosa, Gran Paradiso, Dora-Maira and Valosio), tectonically enveloped by mafic-ultramafic eclogitic slivers (Zermatt-Saas, Grivola, Viso, and Voltri). In the Eclogite belt, quartz-eclogite assemblages prevail, but small tectonic slices including coesite-eclogite assemblages were recognized in the Dora-Maira unit (Brossasco-Isasca slice) [*Chopin et al*., 1991] and at the top of the Zermatt-Saas ophiolites (Cignana slice) [*Reinecke*, 1991; *Frezzotti et al*., 2011]. The southern part of the Eclogite belt is unconformably overlain by the Oligo-Miocene successions of the Tertiary Piedmont Basin (Figure 3a, section Y-Y'), and underwent major counterclockwise rotation during the Neogene opening of the Ligurian-Provençal basin [*Maffione et al*., 2008].

The lower-pressure metamorphic units of the Western Alps are exposed closer to the European mainland, within a Cenozoic doubly-vergent Frontal wedge (section X-X') including blueschist-to-greenschist facies cover sequences (e.g., Lago Nero, Queyras) and basement slivers (e.g., Ambin, Leverogne). Different tectonostratigraphic domains are involved along strike within the Frontal wedge, as a consequence of oblique subduction relative to the European passive margin (cf. Figure 5). To the north (i.e., west of the Gran

Paradiso dome), the frontal part of the wedge includes Valaisan oceanic metasediments with minor ophiolites and upper Paleozoic continental metaclastics [*Polino et al*., 2012], juxtaposed against Briançonnais basement units in the rear part of the wedge [*Malusà et al*., 2005a]. To the south (i.e., west of the Dora-Maira dome), the frontal part of the wedge includes Briançonnais cover sequences [*Barfety et al*., 1996] juxtaposed against Piedmont oceanic metasediments in the rear part of the wedge [*Polino and Lemoine*, 1984; *Malusà et al*., 2002; *Lardeaux et al*., 2006], which are locally capped by subgreenschist facies ophiolites (e.g., Chenaillet unit) and turbidites (e.g., Antola and Parpaillon Helminthoid Flysch) [*Kerckhove*, 1969; *Chalot-Prat*, 2005]. Progressively more distal facies are thus accreted in the Frontal wedge from the north to the south, but the effects of oblique subduction are also observed in the Eclogite belt, where the relative amount of oceanic crust comprised within the domes markedly increases toward the south, and is dominant in the Voltri massif [*Forcella et al*., 1973; *Capponi and Crispini*, 2002].

Along the Western Alps transect, Adria indentation beneath the axial belt is negligible (Figure 3a), unlike in the central Alps where indentation is significant. West of the Frontal Pennine Fault, where continental crust that has escaped Alpine metamorphism is exposed in the External Massifs, shortening is also minor [*Malusà et al*., 2009; *Dumont et al*., 2012]. A major duplex of European crust [*Schmid and Kissling*, 2000] or lithospheric mantle [*Polino et al*., 1990], 10–15 km thick and 30–40 km long, is seismically imaged along the Western Alps transect structurally on top of the lower plate, and beneath the Eclogite belt (section X-X′ in Figure 3a). Mantle exhumed at shallow depth along the Adriatic margin, evidenced by gravity data and classically referred to as the Ivrea Body [*Closs and Labrouste*, 1963; *Rey et al*., 1990], may represent a relict of the lithospheric necking zone on the southern Tethyan margin.

5.1.3. The Alps-Apennines Transition Zone

Further south, along the transition zone with the Northern Apennines, the low-grade Ligurian units exposed east of the Voltri eclogites (Internal and External Ligurian units in Figure 3a) were deformed and metamorphosed before the middle Eocene [*Ellero et al*., 2001; *Marroni et al*., 2001; *Levi et al*., 2006], and were unconformably covered by wedge-top Epiligurian successions beginning in the upper Lutetian-Priabonian [*Catanzariti et al*., 2002, and references therein]. For this reason, they are often ascribed to the Alpine accretionary wedge [*Cerrina Feroni et al*., 2004; *Malusà and Balestrieri*, 2012]. The underlying Subligurian and Tuscan units were instead accreted, since Oligocene times, within the framework of Apenninic subduction and coeval northward motion of the retreating Adriatic microplate. They chiefly include Meso-Cenozoic successions topped by Oligo-Miocene turbidites fed from the exhuming Lepontine dome [*Garzanti and Malusà*, 2008; *Malusà et al*., 2013], originally deposited in the Adriatic foredeep and now exposed in tectonic windows within the Ligurian units (e.g., Apuane and Bobbio windows, Figure 3a, section Z-Z′). East of the Villalvernia-Varzi-Ottone fault, the Oligo-Miocene Apenninic tectonics strongly reshaped the former Paleogene orogenic wedge [*Elter and Pertusati*, 1973; *Malusà and Balestrieri*, 2012]. This major fault is part of a larger Miocene-Pliocene transpressional system near-parallel to the orogenic trend, also including out-of-sequence thrusts and faults [*Cerrina Feroni et al*., 2002, 2004; *Elter et al*., 2011]. Along cross-section Y-Y′, the Villalvernia-Varzi-Ottone fault juxtaposes the N-dipping Tertiary Piedmont succession against the External Ligurian units. Along cross-section Z-Z′, it juxtaposes the uppermost levels of the Paleogene orogenic wedge (Antola, and underlying Internal Ligurian units) against the lowermost External Ligurian units. The Sestri-Voltaggio Fault (SV in Figure 3a), sometimes interpreted as the metamorphic boundary between the Alps and the Apennines, is overlain by Tertiary Piedmont strata, attesting that it was virtually inactive after the Eocene [*Elter and Pertusati*, 1973].

5.2. Geologic Record of (U)HP Rocks Exhumation

5.2.1. Exhumation Paths

In Cenozoic times, rocks now exposed in the Alpine orogenic wedge were either subducted to deep subcrustal levels [*Chopin*, 2003; *Vignaroli et al*., 2005; *Groppo et al*., 2009], detached and subcreted at intermediate crustal levels [*Desmons*, 1992; *Malusà et al*., 2005a; *Lanari et al*., 2014], or offscraped at shallow structural levels thus escaping metamorphism [*Chalot-Prat*, 2005; *Levi et al*., 2006; *Schwartz et al*., 2007]. During subsequent exhumation, deeply subducted rocks were retrogressed at lower pressures and temperatures until they eventually reached the surface.

The typical pressure-temperature paths followed by the exhuming (U)HP units of the Western Alps show an early rapid stage of nearly isothermal decompression, which is followed by slow cooling after an inflection point invariably located at 34–32 Ma (Figure 7a). Peak-pressure assemblages in the Sesia-Lanzo unit are remarkably older than those observed in all of the other units [*Duchêne et al*., 1997; *Rubatto et al*., 1999]. Heating after decompression is documented both in the Lepontine dome [*Brouwer et al*., 2004] and in the continental units of the Eclogite belt [*Borghi et al*., 1996].

Pressure-time paths allow an easier comparison between the exhumation trajectories followed by different units within the subduction zone (Figure 2e). They show that the Frontal wedge displays the oldest peak-pressure parageneses associated with Eocene subduction, with peak pressure generally lower than 1.2–1.4 GPa [*Agard et al*., 2002; *Ganne et al*., 2006; *Malusà et al*., 2005a; *Lanari et al*., 2012]. The youngest peak assemblages are observed in the Eclogite belt, where estimated peak pressure locally exceeds 3 GPa [*Chopin et al*., 1991; *Reinecke*, 1991], which likely indicates burial to subcrustal depths. Units of the Eclogite belt experienced very fast exhumation after 45–40 Ma [*Duchêne et al*., 1997; *Federico et al*., 2005; *Rubatto and Hermann*, 2001; *Rubatto et al*., 1998; *Vignaroli et al*., 2010] and started traveling back to the surface, at rates of 10–30 km/Ma, at the same time as the blueschist-greenschist facies units of the Frontal wedge were already emplaced at shallow crustal levels. Exhumation rates in the Western Alps dropped markedly after 34–32 Ma (Figure 2e), when sediments of the Tertiary Piedmont Basin, including patch reef carbonates [*Fravega et al*., 1987; *Vannucci et al*., 1997], were deposited upon the southern part of the Eclogite belt [*Federico et al*., 2005; *Malusà and Garzanti*, 2012]. Since then, relatively fast exhumation within the axial belt is documented only in the Lepontine dome of the central Alps (up to 1.3–2.0 km/Ma during the late Oligocene-early Miocene) [*Malusà et al*., 2011b].

5.2.2. Strain Partitioning During Subduction and Exhumation

During subduction and exhumation of (U)HP rocks, deformation was strongly partitioned between the major tectonic domains of the Western Alps. On the upper plate side of the subduction system, the western tip of the Cretaceous wedge shows a complex structural pattern that formed in Paleocene times within a regional framework of right-lateral transpression [*Babist et al*., 2006]. Close to the Eclogite belt, these structures are overprinted by left-lateral shear zones, and by transposed greenschist-facies foliations with E-W stretching lineations developed since middle Eocene times [*Inger and Ramsbotham*, 1997; *Malusà et al*., 2006; *Gasco et al*., 2009]. Inclusions in coeval quartz veins show a mixing between rising CO_2-rich fluids and saline fluids infiltrating from the surface [*Malusà et al*., 2006], which suggests that the western tip of the Cretaceous wedge was still below the sea level at that time. Meteoric fluids are found instead in veins postdating the Oligocene Periadriatic magmatism.

In the Frontal wedge, contractional structures are dominant. They define a long-recognized doubly vergent pattern [*Fabre*, 1961], outlined by east-dipping thrusts and Europe-vergent folds in the west [*Freeman et al*., 1998; *Fügenschuh et al*., 1999] and by thick west-dipping shear zones and associated Adria-vergent structures in the east [*Malusà et al*., 2005a; *Michard et al*., 2004]. These structures are cut by steeply dipping left-lateral faults, which are near-parallel to the orogenic trend [*Michard et al*., 2004; *Ricou and Siddans*, 1986] and show to the north evidence of right-lateral reactivation [*Malusà et al*., 2009]. Adria-vergent structures of the Frontal wedge are generally marked by higher-pressure assemblages (up to the blueschist facies) than Europe-vergent structures (greenschist facies or lower), and record early exhumation trajectories during shortening and accretion of crustal material on top of the downgoing European slab [*Malusà et al*., 2011a].

During (U)HP exhumation in the Eocene, widespread synmetamorphic extension occurs in rocks that lie structurally on top of and within the Eclogite belt. Such synmetamorphic extension is often associated with the development of L-tectonites, which are not found inside the Frontal and Cretaceous wedges. On the eastern side of the Eclogite belt, greenschist-facies top-to-SE extensional shearing affected the Combin and Dent Blanche units between 45 and 36 Ma [*Reddy et al*., 2003]. Top-to-NW extension occurred before 34 Ma along the Entrelor shear zone, west of the Gran Paradiso unit [*Malusà et al*., 2005a]. Farther south, greenschist-facies top-to-W extension is documented on top of the eclogitic ophiolites exposed west of the Dora-Maira unit [*Agard et al*., 2002], and in the Queyras calcschists on top of the Viso ophiolites [*Ballèvre et al*., 1990; *Schwartz et al*., 2007]. Extension in the Eclogite belt is associated with a regular pattern of stretching lineations perpendicular to the orogen trend, observed within extensional shear zones both in the Internal Massifs [*Wheeler*, 1991; *Brouwer et al*., 2002; *Pleuger et al*., 2005; *Le Bayon and Ballèvre*, 2006] and in their ophiolitic envelopes [*Philippot*, 1990; *Inger and Ramsbotham*, 1997; *Reddy et al*., 1999; *Gasco et al*., 2009, 2011], which is fully consistent with the trend observed in the overlying Cretaceous wedge [*Gasco et al*., 2009]. On the northern tip of the Eclogite belt, close to the Lepontine dome, late tectonic shortening

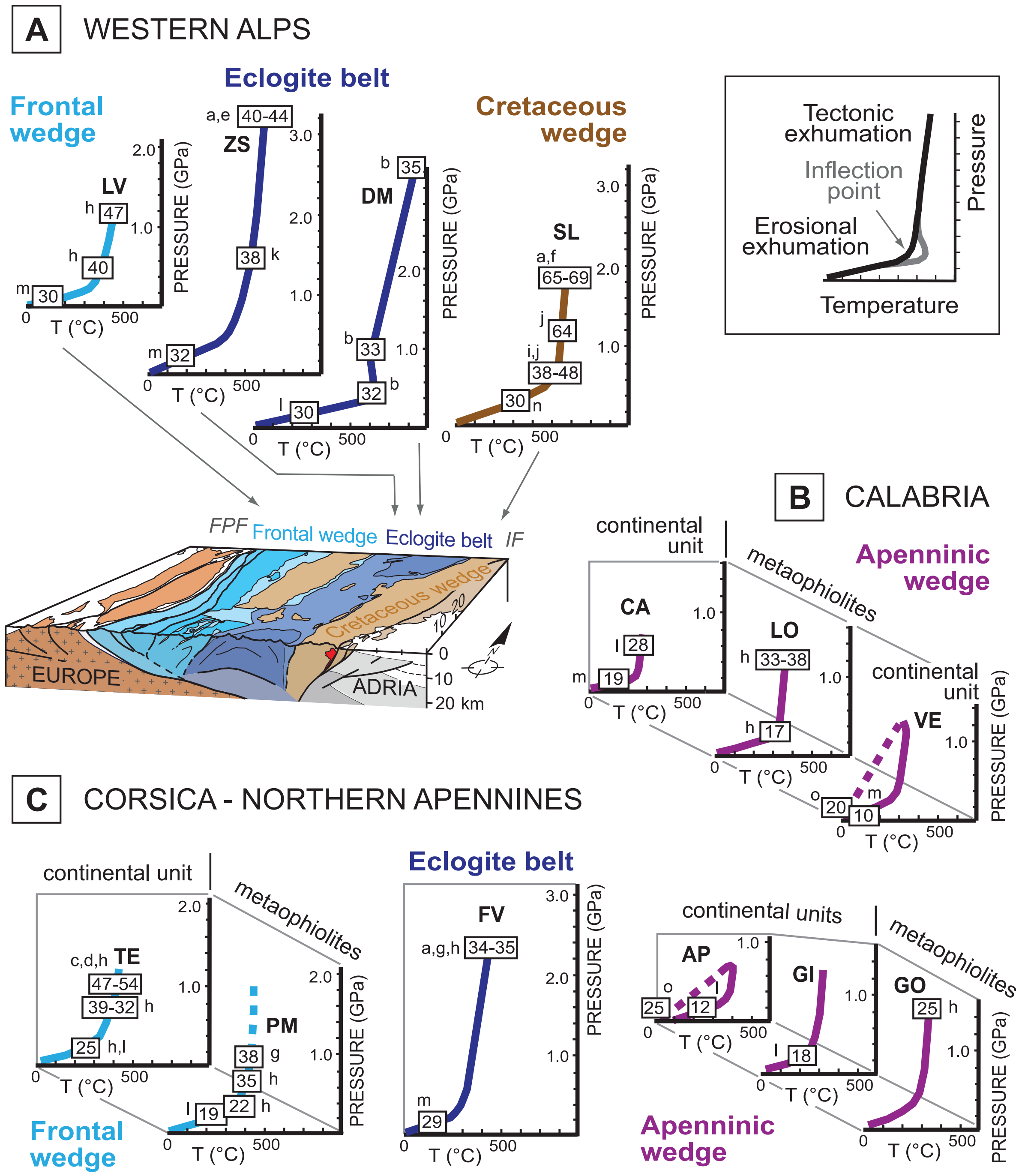

Figure 7. Exhumation pressure-temperature paths, complemented by geochronologic ages unambiguously linked with petrologic and structural data (boxes, in Ma). Sample location in Figure 3. (a) Selected exhumation paths from the Western Alps (see *Malusà et al.* [2011a] and supporting information S1 for additional paths), and typical P-T path for Alpine (U)HP units (inset): DM, Brossasco-Isasca UHP slice, Dora-Maira [*Chopin et al.*, 1991; *Rubatto and Hermann*, 2001]; LV, Leverogne unit, Gran San Bernardo nappe [*Malusà et al.*, 2005a, 2005b; *Villa et al.*, 2014]; SL, Sesia-Lanzo unit, Cretaceous wedge [*Babist et al.*, 2006; *Duchêne et al.*, 1997; *Malusà et al.*, 2006; *Rubatto et al.*, 1999]; ZS, Cignana UHP slice, Zermatt-Saas [*Amato et al.*, 1999; *Malusà et al.*, 2005b; *Rubatto et al.*, 1998]. Three-dimensional model based on the ECORS-CROP seismic section and on the geologic map in Figure 3a (FPF, Frontal Pennine Fault; IF, Insubric Fault). (b) Calabria: CA, Castagna unit, Calabride units [*Thomson*, 1994; *Rossetti et al.*, 2001a]; LO, Gimigliano lower ophiolitic unit [*Thomson*, 1994; *Rossetti et al.*, 2001a]; VE, Lungro-Verbicaro unit [*Iannace et al.*, 2007; *D'Errico and Di Staso*, 2010]. (c) Corsica-Northern Apennines. AP, Apuane, Tuscan metamorphic units [*Balestrieri et al.*, 2003; *Molli and Vaselli*, 2006]; FV, Farinole-Volpajola Unit, Corsica [*Mailhé et al.*, 1986; *Brunet et al.*, 2000; *Ravna et al.*, 2010; *Martin et al.*, 2011; *Vitale Brovarone and Herwartz*, 2013; *Vitale Brovarone et al.*, 2014]; GI, Giglio Island, Tuscan metamorphic units [*Rossetti et al.*, 1999; *Balestrieri et al.*, 2011]; GO, Gorgona Island, Schistes Lustrés metapelites [*Brunet et al.*, 2000; *Rossetti et al.*, 2001b]; PM, Pigno-Morosaglia unit, Corsica [*Brunet et al.*, 2000; *Fellin et al.* 2006; *Vitale Brovarone and Herwartz*, 2013; *Vitale Brovarone et al.*, 2014]; TE, Tenda unit, Corsica [*Brunet et al.*, 2000; *Cavazza et al.*, 2001; *Molli et al.*, 2006; *Maggi et al.*, 2012]. Geochronologic constraints: U-Pb SHRIMP on zircon (a), titanite (b); U-Pb TIMS on acmite-phengite (c), rutile (d); Sm-Nd on garnet-omphacite-paragonite-clinozoisite-glaucophane (e); Lu-Hf on garnet-phengite (f), lawsonite-glaucophane (g); ^{40}Ar-^{39}Ar on white mica (h); Rb-Sr on phengite-calcite (i), phengite-feldspar (j), phengite-whole rock (k); fission tracks on zircon (l), or apatite (m); age of undeformed magmatic bodies (n); biostratigraphic age of sediments (o).

overprinted extensional shearing after (U)HP exhumation, thus shaping regional-scale Adria-vergent folds such as the Vanzone antiform, located NE of the Monte Rosa Massif [*Keller et al*., 2006]. No regional-scale late backfolding is observed in the Internal Massifs located farther south.

5.2.3. Stratigraphic Constraints on (U)HP Exhumation

During (U)HP exhumation, the growing Alpine orogen was bounded to the northwest by a foreland basin built upon European crust [*Sinclair*, 1997], and to the southeast by a foredeep floored by Adriatic crust [*Catanzariti et al*., 1996, 2009; *Elter et al*., 2003] (Figure 5d). Since the middle Eocene, smaller depocentere also developed on top of the orogenic wedge, as indicated by the Tertiary Piedmont and Epiligurid successions [*Mutti et al*., 1995; *Cibin et al*., 2001; *Gelati and Gnaccolini*, 2003; *Bertotti et al*., 2006]. All of these basins were starved of orogenic detritus during exhumation of (U)HP rocks.

In the European (North Alpine) foreland basin, the shallow-marine Nummulite Limestone and overlying Globigerina Marl record deepening of a sediment-starved basin diachronously in the Paleogene [*Ford and Lickorish*, 2004]. Starting from the latest Priabonian, the basin was filled by turbidites such as the Annot Sandstone, chiefly derived from the European basement exposed to the southwest [*Sinclair*, 1997], whereas minor detrital supply from the axial belt is documented since the Oligocene [*Jourdan et al*., 2012, 2013]. The Annot turbidites are unmetamorphosed and still lay on top of the European basement, which was thrust westward only after (U)HP exhumation was completed [e.g., *Bellanger et al*., 2015] (Figure 5e). Such basement-cover relationships exclude slab retreat along the Western Alps trench during exhumation of (U)HP rocks (see Figure 1c). In that case, turbidites would be in fact detached from their basement as observed in the Apennines.

In the Adriatic foredeep, starved sedimentation after Paleocene-Eocene deposition of pelagic marls (Scaglia Fm) is recorded by the middle Eocene-lower Oligocene Gallare Marl and Chiasso Fm to the north [*Di Giulio et al*., 2001], and by the Canetolo Complex and Aveto Fm to the south [*Catanzariti et al*., 1996]. Volcaniclastic supply characterized this otherwise starved stage, both in the North Alpine basin and in the Adriatic foredeep, during the Oligocene climax of Periadriatic magmatism [*Elter et al*., 1999; *Malusà et al*., 2011b; *Ruffini et al*., 1997].

The only depocenters fed by detritus from the axial belt before the Periadriatic climax are the small sedimentary basins developed on top of the orogenic wedge [*Ottria*, 2000; *Cibin et al*., 2001; *Cerrina Feroni and Vescovi*, 2002; *Gelati and Gnaccolini*, 2003; *Jourdan et al*., 2012]. In the Tertiary Piedmont basin, the stratigraphic relations between HP rocks, and sediments derived from their erosion, are unambiguously preserved on top of the Voltri and Valosio units, where the dominant antigorite-serpentinite clasts in the lower Oligocene Molare and Rocchetta Fms demonstrate that metaophiolites were already exhumed and eroded by the end of the Eocene. Calcareous nannoplankton assemblages point to a stratigraphic age of 32–30 Ma for the Rocchetta Fm (NP23 nannozone) [*D'Atri et al*., 1997; *Maffione et al*., 2008; *Ghibaudo et al*., 2014]. This age is consistent with the Rupelian age ($\sim$30 Ma) provided by planktonic foramnifera in the Rocchetta Fm basal strata (P20 biozone) [*Gnaccolini et al*., 1990], and with the early Rupelian age provided both by larger (benthic) foramnifera (32 $\pm$ 2 Ma, SBZ 21 zone) [*Vannucci et al*., 1997, 2010] and by dinoflagellate stratigraphy (32 $\pm$ 1 Ma, *W. gochtii* zone [M. *Rossi et al*., 2009]) in the underlying Molare Fm (biozones according to *Gradstein et al*. [2004, and references therein]). Corals on top of the Voltri metaophiolites [*Vannucci et al*., 1997; *Quaranta et al*., 2009] and of the Antola flysch sediments [*Carnevale et al*., 2003] attests to orogenic wedge exposure close to the sea level, while pollen data indicate that the Frontal wedge already represented a topographic high in the early Oligocene [*Fauquette et al*., 2015].

Massive influx of orogenic detritus from the Alpine accretionary wedge reached the North Alpine basin and the Adriatic foredeep no earlier than the latest Oligocene [*Gelati et al*., 1988; *Schlunegger*, 1999], synchronous with topographic growth of the central Alps [*Gansser*, 1982] (Figure 5). In the Adriatic foredeep, the Gonfolite-Macigno clastic wedge (upper Oligocene-lower Miocene) was chiefly fed by focused erosion of medium-grade rocks of the Lepontine dome and the encased Bregaglia pluton, with minor detritus supplied from the axial Western Alps [*Garzanti and Malusà*, 2008; *Malusà et al*., 2011b; *Dafov et al*., 2014].

5.2.4. Plate Motion Constraints

The metamorphic, structural, and stratigraphic record in the Western Alps suggests divergence within the subduction zone during exhumation of (U)HP rocks (cf. Figure 1). Available kinematic constraints [e.g., *Dewey et al*., 1989; *Jolivet et al*., 2003], when analyzed within the framework of recent palinspastic reconstructions [*Malusà et al*., 2015], confirm that Adria motion shows no convergence along the Western Alps

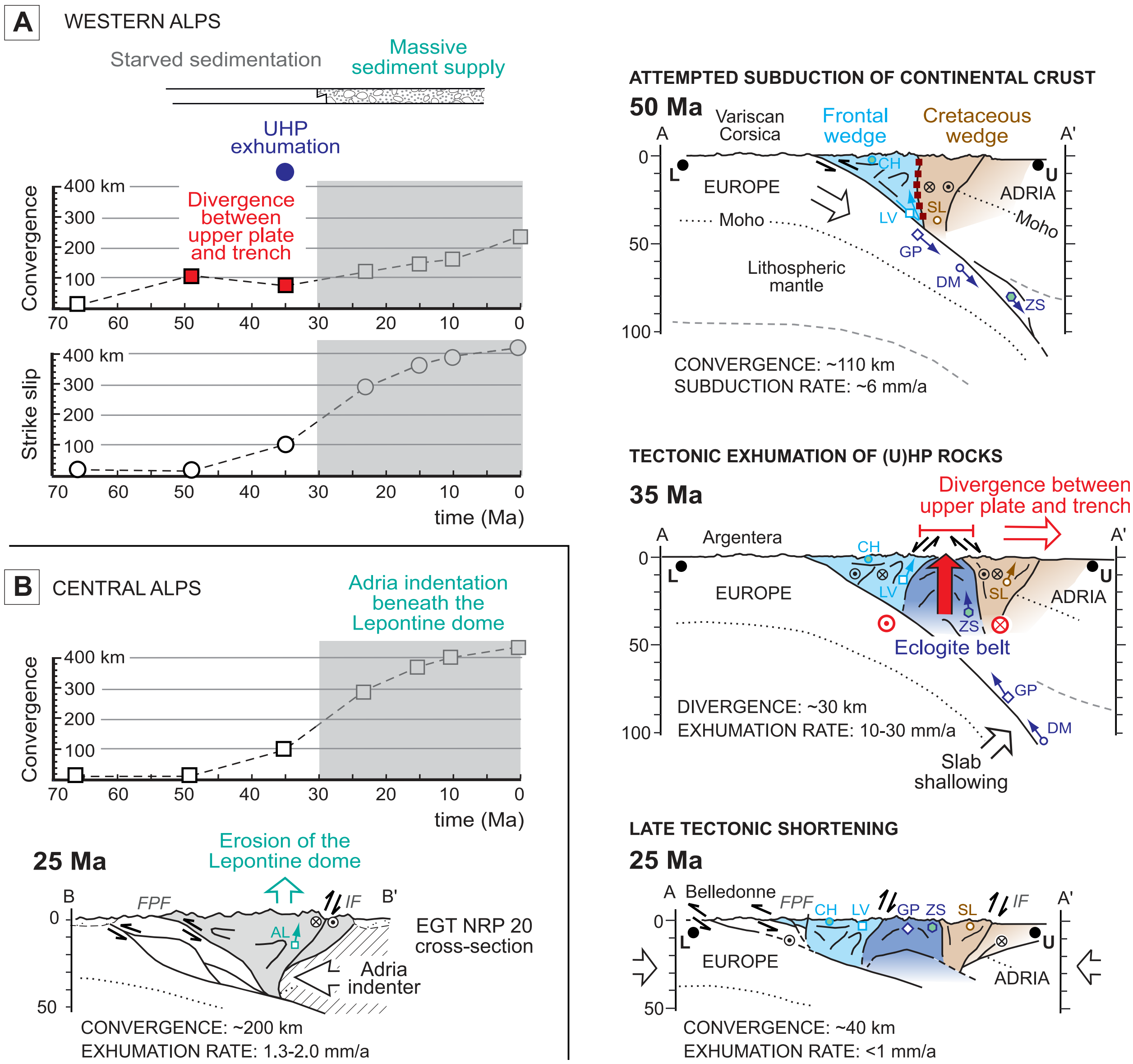

Figure 8. Exhumation driven by the upper plate (Western Alps). (a) (left) Trench-normal and trench-parallel components of Adria-Europe relative motion, and comparison with the stratigraphic record and the (U)HP exhumation timing in the Tertiary Western Alps; components of plate motion are derived from displacement trajectories in Figure 5, square size encompasses uncertainties in plate motion deconvolution; the grey area indicates convergence and strike-slip possibly accommodated outside the subduction zone. Note that trench-normal divergence (bracketed by red squares) and starved sedimentation are coeval with fast exhumation of the Eclogite belt (blue dot). (right) Restored cross sections along the ECORS-CROP traverse in three steps (acronyms as in Figure 3); the amount of trench-normal convergence is referred to fixed points on lower (L) and upper (U) plates (modified after *Malusà et al.* [2011a]): Step 1 (Paleocene-early Eocene): convergence is near-perpendicular to the trench (Figure 5c for map view), crustal material is progressively accreted in the Frontal wedge or deeply subducted (unlike steps 2 and 3, (U)HP rocks are not indicated in blue to take into account uncertainties in pressure-to-depth conversion). Step 2 (middle-late Eocene): Adria motion away from the trench (Figure 5d for map view) induces localized extension within the weak portion of the upper plate; the Eclogite belt is exhumed up to the surface at rates much faster than subduction rates; erosion is minor, adjacent basins remain starved. Step 3 (Oligocene): oblique convergence replaces oblique divergence (Figure 5e for map view), and is accommodated by crustal shortening; axial-belt detritus reaches sedimentary basins. (B) trench-normal component of Adria-Europe relative motion in the central Alps, and restored cross section along the EGT NRP 20 traverse (based on *Pfiffner et al.* [2002]); unlike the Western Alps, no episode of divergence characterized this segment of the subduction zone; the fast post-Eocene erosional unroofing of the Lepontine dome (cf. Figure 2e) is ascribed to Adria indentation beneath the axial belt.

trench in this time frame (Figure 5d), but is instead characterized by high obliquity associated to a slight motion away from the trench. Adria-Africa moved northward relative to Europe during most of the Cenozoic, and the Western Alps experienced strike-slip tectonics during most of their evolution, with dominant E-W convergence restricted to the 67–49 Ma time interval (Figure 5c).

In Figure 8a, the predicted amount of convergence at the Western Alps trench, based on the rotation poles of *Dewey et al.* [1989], is deconvolved into a trench-normal and into a trench-parallel component to evaluate the amount of shortening and strike-slip motion accommodated along the paleotrench over time. Bias due to uncertainties in paleotrench orientation, which is strongly controlled by the configuration inherited from the Adriatic passive margin, is possibly minor because this configuration is reasonably well constrained south of the Alps [e.g., *Winterer and Bosellini*, 1981; *Fantoni and Franciosi*, 2010]. If the kinematic model is correct (see *Jolivet and Faccenna* [2000] and *Jolivet et al*. [2003] for more recent applications), the estimated Cenozoic trench-normal convergence that was accommodated before choking of Alpine subduction is on the order of 100 km, and includes ~30 km trench-normal divergence bracketed between 49 and 35 Ma. In the same time span, the amount of sinistral strike-slip motion accommodated along the N-S paleotrench of the Western Alps is much higher, on the order of 200 km. In the E-W paleotrench of the central Alps, 200 km of trench-normal convergence does not include major episodes of trench-normal divergence (Figure 8b).

5.3. Evolution of the Western Alps Subduction Zone

The above geologic constraints for the Western Alps subduction zone consistently indicate (U)HP rock exhumation facilitated by the motion of the upper plate away from the trench (case (ii) in Figure 1).

In Paleocene-early Eocene times (first time frame in Figure 8a), plate motion constraints imply ~110 km convergence and minor strike slip motion along the active margin of the Western Alps. The first attenuated European crust arrived at the Western Alps trench no later than the earliest Paleocene (~65 Ma) and was buried at rates of 3–4 mm/a during the prograde path, reaching mantle depths by the late Eocene (~35 Ma) as indicated by petrologic and geochronologic data [e.g., *Rubatto and Hermann*, 2001]. During subduction, crustal material was progressively accreted in the Frontal wedge locally reaching blueschist facies conditions (e.g., Leverogne unit, LV in Figure 8a), to be subsequently exhumed along eastward trajectories on the rear part of the Frontal wedge [e.g., *Malusà et al*., 2005a; *Lanari et al*., 2014]. Slivers of oceanic crust (e.g., Zermatt-Saas unit, ZS in Figure 8a), followed by slivers of thinned continental crust (e.g., Dora-Maira and Gran Paradiso units, DM and GP in Figure 8a), were deeply subducted, metamorphosed under eclogite-facies conditions, eventually detached from the lower plate, and underplated at depth beneath the upper plate. Sediments were only occasionally dragged down to great depth, as indicated by the small amount of exhumed (U)HP metasediments in the Eclogite belt, compared to widespread cover sequences accreted in the Frontal wedge along the same transect.

In the middle-late Eocene, NNE-ward Adria motion caused a significant kinematic change along the Western Alps subduction zone (Figure 5d). Left-lateral motion was dominant in this time interval, and was associated with ~30 km trench-normal divergence (Figure 8a). This is an extremely important point with respect to (U)HP exhumation, as the divergence provided sufficient space to allow the exhumation and subsequent emplacement of the whole Eclogite belt in the upper crust without any overburden removal by erosion. Eclogitic crustal slivers, previously underplated at depth beneath the upper plate, experienced rapid buoyancy-driven uplift. The density of eclogitized granitoid rocks after subduction (~3.0 kg/dm^3) was less than the density of the nearby mantle rocks (~3.2 kg/dm^3), and their density further decreased during retrogression and exhumation toward the upper crust (~2.7 kg/dm^3). Metabasaltic eclogites, although denser than mantle rocks (~3.7 versus ~3.2 kg/dm^3), were associated with low-density serpentinites (~2.6 kg/dm^3) that greatly increased their overall buoyancy [e.g., *Schwartz et al*., 2001]. Slab shallowing following upper plate divergence provided an additional mechanism to facilitate fast exhumation of (U)HP rocks through the accretionary wedges (i.e., Frontal and Cretaceous), where exhuming units became neutrally buoyant (Figure 8a). The Eclogite belt was thus tectonically emplaced within the upper crust, on the upper plate side of the orogen, and rapidly exposed at the surface beneath opposite-dipping extensional shear zones, and then was finally covered by lower Oligocene sediments. Exhumation was much faster than subduction [cf. *Rubatto and Hermann*, 2001], with exhumation rates locally exceeding 30 mm/a [e.g., *Duchêne et al*., 1997], i.e., 1 order of magnitude higher than average burial rates during the prograde path. It is important to emphasize that during tectonic exhumation of the Eclogite belt the role of erosion was negligible, and foreland basins surrounding the orogen remained starved of sediment (cf. Figure 1).

Rapid exhumation of (U)HP rocks ceased by the end of the Eocene, when Adria started moving NNW-ward with respect to Europe, and the component of trench-normal divergence was replaced by a component of trench-normal convergence (Figure 5e). This turning point corresponds to the transition between nearly isothermal decompression and slower cooling recorded by P-T-t paths. After the

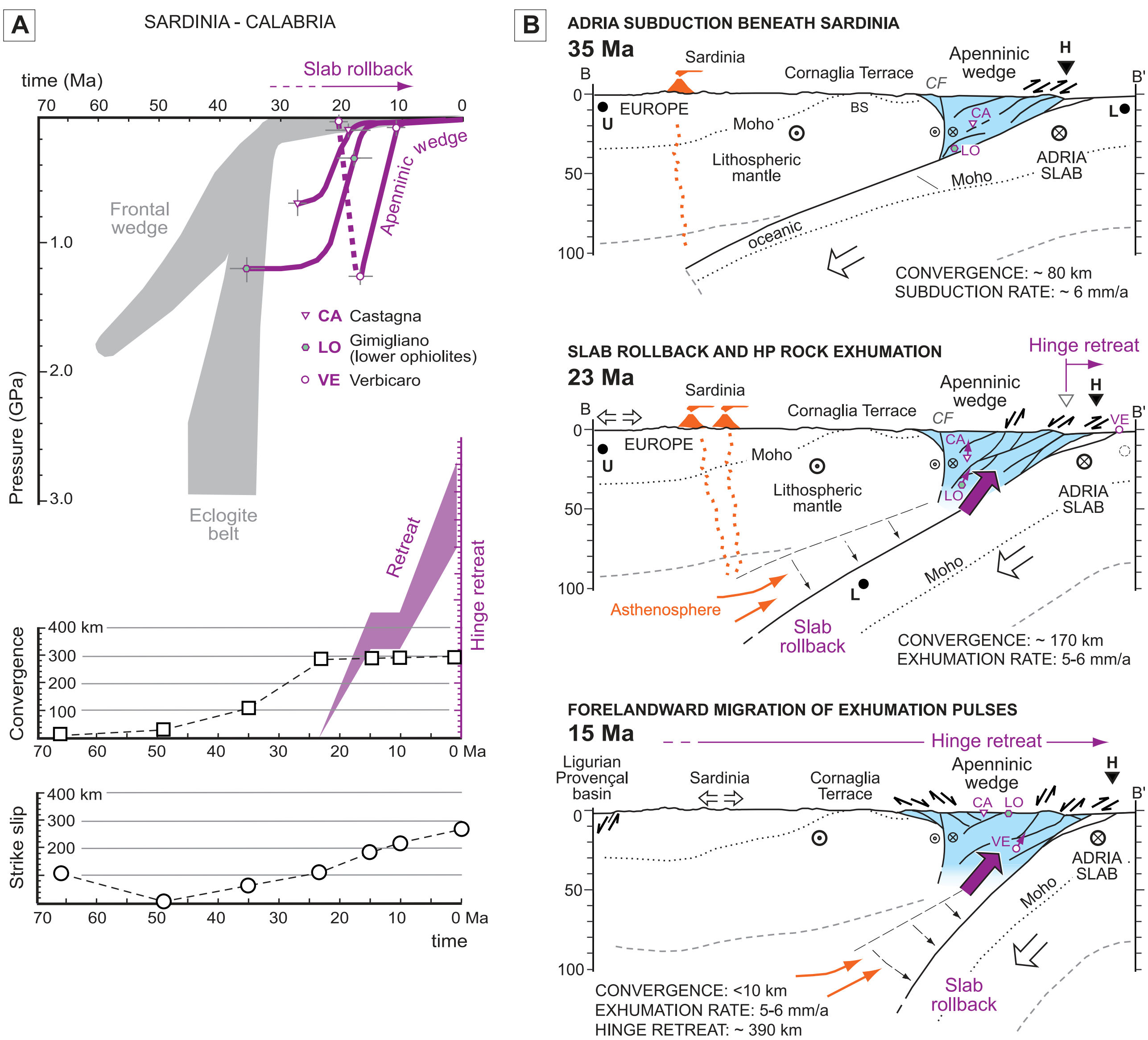

Figure 9. Exhumation driven by the lower plate (Calabria). (a) (top) Comparison between exhumation paths, and (bottom) trench-normal and trench-parallel components of Adria-Europe relative motion along the Sardinia-Calabria transect (same keys as in Figure 8, acronyms as in Figure 3). Components of plate motion are derived from displacement trajectories in Figure 5. Pressure-time paths are based on data in Figure 7b, error bars indicate uncertainties on mineral ages ($\pm 1\sigma$) and pressure ranges for specific mineral assemblages (bias of depth conversion by assuming purely lithostatic pressure is well within the large error of pressure estimates). Note that: exhumation in Calabria (purple) is younger than in the Western Alps (grey areas, cf. Figure 2e), and coeval with rollback of the Adriatic plate; exhumation pulses young toward the foreland during the retreat of the subduction hinge; subduction is largely due to convergence during the Paleogene, and to hinge retreat during the Neogene. (b) Restored cross sections along the Sardinia-Calabria traverse in three steps (based on *Rossetti et al.* [2001a, 2004], *Piana Agostinetti and Amato* [2009], *Minelli and Faccenna* [2010], *Vignaroli et al.* [2012], and *Malusà et al.* [2015]).Step 1 (Eocene-Oligocene): the Adriatic slab is subducted beneath the remnants of the northern Tethyan margin (Figure 5d for map view); ophiolites (LO) are accreted beneath the Calabride units (CA), the slab reaches a depth consistent with the onset of orogenic magmatism in NW Sardinia. Step 2 (latest Oligocene-early Miocene): the onset of slab rollback (Figure 5e for map view) triggers detachment-style extension in Calabria leading to exhumation of HP ophiolites (purple arrow), and the climax of orogenic magmatism in Sardinia. Step 3 (middle Miocene): a younger exhumation pulse, still related to Adriatic slab retreat before its drastic deceleration at ~10 Ma, is recorded toward the foreland by the Apenninic-Maghrebian units (VE), which were still at the surface during metamorphism of HP ophiolites.

deceleration in exhumation rate, and cessation of active subduction along the trench, relaxation of isotherms-induced late-stage heating of the continental eclogitic units, and led to a progressive increase in geothermal gradients. Adria-Europe convergence continued throughout the Neogene. It was strongly partitioned across the orogen and chiefly accommodated in the external zones by frontal thrusting [*Malusà et al.*, 2009; *Dumont et al.*, 2012], leading to a progressive relief development [e.g., *Fauquette et al.*, 2015] until the European margin was deeply underthrust beneath the axial belt and shortening started propagating to the Jura mountains.

While the Western Alps were the site of major Eocene-Oligocene strike-slip motion, the central Alps were dominated by convergence during most of the Tertiary (Figure 8b). Convergence in the central Alps was initially accommodated by subduction, coupled with upper crustal shortening on the European side of the orogen, and later by indentation of Adriatic lithosphere beneath the axial belt. Indentation led to the erosional unroofing of the Lepontine dome, with consequent delivery of a massive detrital supply toward the Adriatic foredeep.

6. Exhumation Driven by the Lower Plate: Calabria

The Calabria orogenic segment (Figure 3c), lying atop the retreating west-dipping Adriatic slab, preserves a different geologic record of HP rock exhumation as compared to the Western Alps (case (iii) in Figure 1). This orogenic segment, also referred to as the Calabrian Arc, includes an onshore-to-offshore accretionary prism, up to 35–38 km thick at the drainage divide [*Di Stefano et al*., 2009; *Piana Agostinetti and Amato*, 2009]. This accretionary prism was subsequently reactivated by extensional processes along the Tyrrhenian side [*Cello et al*., 1996; *Iannace et al*., 2007, *Rossetti et al*., 2004; *Vignaroli et al*., 2012]. The prominent arcuate shape of the Calabrian Arc was acquired between the end of the Ligurian-Provençal spreading in the Serravallian, and the opening of the Tyrrhenian Sea in the late Miocene-Pleistocene [*Cifelli et al*., 2007; *Mattei et al*., 2007]. Subduction along the Calabria transect, largely exceeding 1000 km, is mainly due to hinge retreat and additionally accommodates ~300 km convergence (Figure 9a).

The uppermost tectonic units exposed in Calabria largely consist of crystalline basement nappes, also referred to as the Calabride units (Figure 3c). The Calabride units form imbricated kilometer-scale thrust sheets with the highest grade rocks structurally above the lowest grade rocks [*Amodio-Morelli et al*., 1976; *Ghisetti and Vezzani*, 1981; *Van Dijk et al*., 2000; *Bonardi et al*., 2001; *Caggianelli and Prosser*, 2001]. They include amphibolitic to granulitic metamorphic rocks [e.g., *Borsi et al*., 1976; *Schenk*, 1980; *Graessner and Schenk*, 2001] that are common along the Adriatic margin of the Tethys, but are generally absent on the European side. The lowermost part of the Calabride nappe stack (Castagna and Bagni units) displays an intense post-Variscan low-grade blueschist facies overprint [*Piccarreta*, 1981; *Rossetti et al*., 2001a], possibly developed during the northeastward motion of Adria near-parallel to the Tethyan margin of Sardinia (Figure 5). In contrast, the uppermost Calabride units resided at shallow depths ($<$7 km) since the late Paleozoic, and experienced relatively rapid exhumation to the surface in Neogene times [*Thomson*, 1994, 1998] following the onset of slab retreat. These units were eventually buried beneath Tortonian sediments (Stilo Capo d'Orlando and Albidona Fms).

The paleotectonic collocation of the Calabride units has been either attributed to the African margin [*Amodio-Morelli et al*., 1976; *Grandjacquet and Mascle*, 1978; *Scandone*, 1982], to the European margin [*Ogniben*, 1973; *Dietrich*, 1988; *Rossetti et al*., 2001a], or to a microcontinent(s) in between [e.g., *Vai*, 1992; *Guerrera et al*., 1993; *Perrone*, 1996; *Bonardi et al*., 2001]. Preservation of the distal northern Tethyan margin and of exhumed subcontinental mantle offshore Sardinia (Cornaglia Terrace) suggests that the Calabride units may represent former extensional allochthon(s) originally located farther to the SE [*Malusà et al*., 2015]. Differences in nappe architecture between northern and southern Calabria, the former showing both Europe and Adria verging structures and the latter exclusively Adria-verging structures, led to the suggestion that these orogenic segments may represent two subterranes with distinct Cretaceous-Paleogene tectonometamorphic evolution, juxtaposed only in Oligocene times [*Bonardi et al*., 2001]. However, recent works indicate that northern and southern Calabria had a common orogenic polarity toward the Adriatic foreland during crustal thickening and nappe stacking [*Rossetti et al*., 2001a, 2004; *Vignaroli et al*., 2008b, 2012], which indicates that Calabria might instead represent a single terrane.

Cenozoic HP rocks are found in northern Calabria at the base of the nappe stack, beneath the Calabride units. They include Ligurian-derived metaophiolites and Adria-derived Apenninic-Maghrebian units (e.g., Verbicaro and San Donato units) [*Ogniben*, 1973; *Cello et al*., 1996; *Rossetti et al*., 2001a, 2004], which provided peak P-T conditions of 1.1–1.3 GPa and ~350°C [*Rossetti et al*., 2001a, 2004; *Iannace et al*., 2007; *Vitale et al*., 2013], similar to those observed in the Frontal wedge of the Western Alps. These values largely exceed the peak P-T estimates for the overlying Calabride units, reaching 0.4–0.6 GPa and $<$300°C in the Castagna unit [*Rossetti et al*., 2001a] (Figures 7b and 9a).

The thrust system of northern Calabria involves not only basement rocks, but also sedimentary units including Mesozoic continental redbeds, Cenozoic shelf limestones, slope shales and deep-sea turbidites (Longobucco cover in Figure 3c) [*Lorenzoni et al*., 1978]. The youngest unit involved within the thrust edifice is Aquitanian in age (Paludi Fm) [*Bonardi et al*., 2005]. The Rossano and Crotone-Spartivento wedge-top basins, unconformably resting on top of the thrust edifice, include alluvial and fan-delta conglomerates overlain by Serravallian(?)-Tortonian fossiliferous sandstones, passing upward to deeper water marls and clays [*Critelli*, 1999]. The age of thrusting in the frontal part of the wedge is thus bracketed between the Aquitanian and the Serravallian-Tortonian [*Cavazza and De Celles*, 1998; *Barone et al*., 2008; *Vignaroli et al*., 2012]. Therefore, Neogene accretion in Calabria occurred without the presence of a backstop [*Minelli and Faccenna*, 2010], as the fore-arc region was flanking at that time a back-arc spreading center (see section 4.3).

Miocene shortening on the Ionian side of the Calabrian Arc was concomitant with extensional tectonics and HP rock exhumation on the Tyrrhenian side [*Vignaroli et al*., 2012], where detachment-style extension overprinted early Adria-directed nappe stacking, stretching apart the previously structured nappe edifice [*Rossetti et al*., 2001a, 2004] (Figure 9b). Exhumation of HP ophiolites was completed in the middle Miocene, after the onset of slab retreat, as indicated by the presence of ophiolitic pebbles in the Miocene clastic sequences lying unconformably atop the Coastal Range (Amantea basin) [*Rossetti et al*., 2001a]; only Calabride nappe pebbles are instead observed in the Stilo-Capo d'Orlando deposits of the Sila area [*Bonardi et al*., 1980; *Cavazza*, 1989]. A younger exhumation pulse, still related to Adriatic slab retreat before its abrupt deceleration at ∼10 Ma [*Faccenna et al*., 2001b], is recorded forelandward by the Apenninic-Maghrebian units (VE in Figure 9b), which were still at the surface during metamorphism of HP ophiolites. High spreading rate was reestablished in the back-arc region a few million years later, during the opening of the Vavilov (6–4 Ma) and Marsili basins (2–1 Ma).

Topographic development in Calabria chiefly postdates exhumation of HP rocks. Uplift to form the modern day topography started in the early Pliocene, as indicated by stratigraphic and structural relationships in the fore-arc basin, and accelerated during the Pleistocene as recorded by marine terraces sculpted into basement rocks [*Bonardi et al*., 2001; *Ferranti et al*., 2006]. As in the Western Alps, erosion thus played a minor role during HP rock exhumation (Figure 1, case (iii)).

7. Upper Versus Lower Plate Control on Exhumation: The Corsica Transect

Corsica represents the northern part of the Corsica-Sardinia continental block, which is bounded by the Ligurian-Provençal basin to the west and by the Tyrrhenian basin to the east (Figure 4). It largely consists of Paleozoic rocks (Variscan Corsica [*Matte*, 1991; *P. Rossi et al*., 2009]), but also includes, to the NE, a Cenozoic HP wedge classically referred to as the Alpine Corsica (Figure 3b) [*Durand-Delga*, 1984; *Caron*, 1994]. Subduction and exhumation of HP rocks in Alpine Corsica has long been debated [*Jolivet et al*., 1990; *Molli and Malavieille*, 2011], and it has been either associated with Alpine dominant south-eastward subduction [e.g., *Mattauer et al*., 1981; *Malavieille et al*., 1998; *Vitale Brovarone et al*., 2013] or with Apenninic northwestward subduction [e.g., *Principi and Treves*, 1984; *Jolivet et al*., 1998; *Vitale Brovarone and Herwartz*, 2013]. Like in the Western Alps, HP units are exposed in tectonic domes, at the rear of a doubly vergent accretionary wedge also including the Tenda unit (J-J' in Figure 3) [*Durand-Delga*, 1984]. These domes are characterized by peak P-T conditions up to 2.4 GPa and ∼450°C (FV in Figure 7c) [*Ravna et al*., 2010; *Vitale Brovarone et al*., 2013], and chiefly include oceanic basement and cover rocks with only minor gneiss slivers. The minor amount of gneiss found within the domes is in line with the observation that the relative amount of continental crust involved in the Alpine subduction zone decreases toward the south, as subduction was oblique relative to the northern Tethyan margin [*Malusà et al*., 2015]. Lower-pressure rocks of Alpine Corsica are chiefly exposed in a doubly vergent frontal wedge closer to the European basement and, in places, overlay the HP rocks exposed on the Tyrrhenian side of the island [*Durand-Delga*, 1984; *Molli*, 2008]. Metamorphic grade increases from the west toward the east: the frontal part of the lower-pressure accretionary wedge includes very low grade ophiolites and flysch units (Balagne Nappe) and minor slices of European continental crust [*Nardi et al*., 1978; *Malasoma et al*., 2006], whereas the rear part includes greenschist-to-blueschist facies ophiolites and continental units (e.g., Pigno-Morosaglia and Tenda units) [*Lahondère*, 1996; *Molli and Tribuzio*, 2004; *Rossetti et al*., 2015].

Alpine Corsica and the Western Alps share not only a similar tectonic configuration but also a similar timing of exhumation (Figure 10b). Tectonic units exposed in the Frontal wedge of Alpine Corsica display the oldest peak-pressure parageneses grown during Cenozoic subduction, and peak pressures generally lower than 1.4 GPa (e.g., Tenda and Pigno-Morosaglia units) [*Maggi et al*., 2012; *Vitale Brovarone et al*., 2013]. The

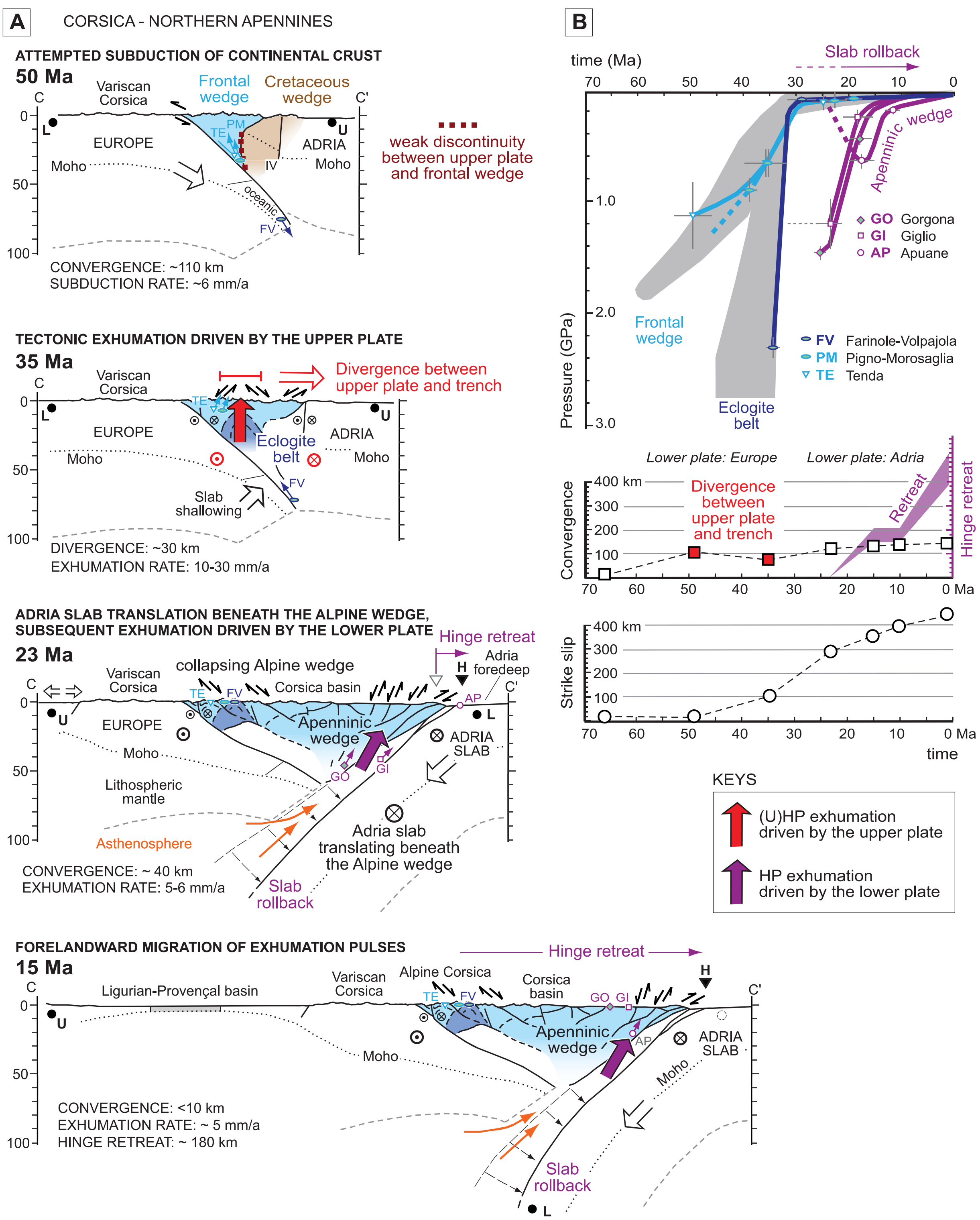

Figure 10.

youngest peak assemblages are described in the HP units on the Tyrrhenian side, where estimated peak pressure may largely exceed 2 GPa (e.g., Farinole-Volpajola unit) [*Brunet et al*., 2000; *Martin et al*., 2011; *Vitale Brovarone and Herwartz*, 2013]. As in the Western Alps, eclogitic units in Corsica experienced very fast exhumation since 35 Ma. They returned to the surface at rates as high as 30 km/Ma, at the same time the blueschist-greenschist facies units of the Frontal wedge were already emplaced at shallow crustal levels [*Rossetti et al*., 2015] (Figure 10b).

Deformation during subduction and exhumation of Alpine Corsica was strongly partitioned between different tectonic domains. In the Frontal wedge, contractional structures are dominant, and define a doubly vergent pattern outlined by east-dipping thrusts to the west [*Egal*, 1992], and by Adria vergent structures to the east [*Rossi et al*., 1994; *Molli et al*., 2006]. Major left-lateral slip was accommodated by steeply dipping faults parallel to the orogen trend (e.g., Ostriconi fault) [*Jourdan*, 1988; *Lacombe and Jolivet*, 2005], as indeed observed in the Frontal wedge of the Western Alps. Widespread synmetamorphic extension, associated with E-W stretching lineations, is documented on the top of, as well as inside the HP units on the Tyrrhenian side [*Malavieille et al*., 2011]. Unlike the Western Alps, no major late tectonic shortening affected the HP tectonic domes, but on the contrary detachment style extension overprinted the early Alpine nappe stacking [*Jolivet et al*., 1990; *Daniel et al*., 1996], leading to the development of major east-dipping shear zones (e.g., the Tenda shear zone in Figure 3b). The age of late extensional deformation, based on Rb-Sr geochronology, is $\sim$20–21 Ma [*Rossetti et al*., 2015].

Stratigraphic data provide accurate constraints on the topographic growth of Alpine Corsica. European foreland successions of Corsica still lie unconformably on top of their Variscan basement [*Rossi et al*., 2001]. This excludes, like in the Western Alps, any major European slab retreat during exhumation of (U)HP rocks (see Figure 1). Synorogenic clastic successions of Cretaceous-to-Eocene age are partly accreted in the frontal part of the wedge [*Egal*, 1992], and locally folded unconformably on top of the Alpine metamorphic units on the rear side [*Rossi et al*., 1994; A. Botti, Le arenarie di P.ta de l'Acciolu (Corsica settentrionale) e il loro substrato cristallino: Successione stratigrafica, assetto strutturale e vincoli desunti dall'analisi di tracce di fissione, unpublished BSc thesis, University of Milano-Bicocca, Milan, Italy, 2010]. Detritus was chiefly derived from the European basement exposed to the SW [*Nardi et al*., 1978; *Marroni and Pandolfi*, 2007; *Malusà et al*., 2015], which indicates that Alpine Corsica, like the Western Alps, was not a major source of detritus during during nappe stacking, and was probably characterized by relatively low topography during most of the Alpine orogeny [*Malusà et al*., 2011c].

We can thus conclude that metamorphic, structural, and stratigraphic data consistently demonstrate that Alpine Corsica was largely structured within the framework of Alpine subduction. Before Neogene opening of the Ligurian-Provençal basin, Alpine Corsica together with the Western Alps was a continuous orogenic segment. As in the Western Alps, exhumation of HP tectonic domes of the Alpine Corsica can thus be ascribed to divergence between upper plate and trench (case (ii) in Figure 1). However, HP rocks are observed not only in the main Corsica island, but also farther to the east in the small islands of the northern Tyrrhenian Sea (e.g., GI and GO in Figure 4) and on the rear side of the Northern Apennines range (e.g., AP, PI, and MO in Figure 4) [*Rossetti et al*., 1999, 2001b; *Balestrieri et al*., 2011]. Peak P-T conditions in HP ophiolites of the Gorgona Island, and in the Adria-derived metamorphic units of the Giglio Island, are on the order of 1.2–1.5 GPa and 300–350°C [*Brunet et al*., 2000; *Rossetti et al*., 1999, 2001b; *Balestrieri et al*., 2011] (Figure 7c). Farther east, the metamorphic Adriatic-foredeep turbidites (Pseudomacigno Fm) exposed in the Apuane tectonic window experienced metamorphic peak conditions of 0.6–0.7 GPa and 350–450°C [*Balestrieri et al*., 2003; *Molli and Vaselli*, 2006]. Although P-T conditions, in all of these units, are comparable with

Figure 10. Upper versus lower plate control on exhumation (Corsica-Northern Apennines). (a) Restored cross sections along the Corsica-Northern Apennines transect, showing the relationships between the Alpine and Apenninic orogenic wedges (same keys as in Figures 8b and 9b). Step 1 (Paleocene-early Eocene): Adria initially acts as the upper plate of the subduction system; convergence is near-perpendicular to the trench (Figure 5c for map view); crustal material is progressively accreted in the Frontal wedge of Alpine Corsica, while oceanic crust is deeply subducted. Step 2 (middle-late Eocene): Adria motion away from the trench induces localized extension within the weak portion of the upper plate (Figure 5d for map view), and the Eclogite belt is exhumed up to the surface. Step 3 (Oligocene-early Miocene): the Alpine orogenic wedge is progressively involved in Adriatic subduction propagating from the south, and it is juxtaposed to the Apenninic wedge; the onset of slab rollback triggers detachment-style extension in the Alpine wedge, and exhumation of HP rocks (GO, GI) in the Apenninic wedge. Step 4 (middle Miocene): a younger exhumation pulse, still related to Adriatic slab retreat, is recorded forelandward by the Adriatic turbidites (AP), which were still at the surface during peak metamorphism in the Tuscan archipelago (GO, GI). (b) (top) Comparison between exhumation paths, and (bottom) components of Adria-Europe relative motion along the Corsica-Northern Apennines transect (same keys as Figure 9a). Note that, in Alpine Corsica, exhumation timing match with the Western Alps (grey areas): HP ages are systematically younger in the Eclogite belt (FV) than in the Frontal wedge (PM, TE), fast exhumation of the Eclogite belt is coeval with trench-normal divergence (Case (ii) in Figure 1). Exhumation timing in Tuscan archipelago (GO, GI) and Northern Apennines (AP) is not consistent with the Alpine evolution observed to the west. Like in Calabria, exhumation is coeval with rollback of the Adriatic plate, and exumation pulses young toward the foreland during retreat of the subduction hinge (Case (iii) in Figure 1).

those documented in the Alpine Frontal wedge (e.g., Tenda unit), their timing of exhumation is not consistent with the Alpine evolution observed to the west. Conversely, timing of exhumation in the northern Tyrrhenian Sea and in the Northern Apennines has many analogies with the evolution observed in Calabria, where exhumation of HP rocks was driven by rollback of the Adriatic slab (case (iii) in Figure 1). Exhumation is in fact coeval with Adria slab rollback also in the Gorgona and Giglio islands, where it was largely completed by the early Miocene. A younger exhumation pulse at $\sim$15 Ma, still related to Adriatic slab retreat, is recorded forelandward in the Apuane Alps by the Adriatic-foredeep turbidites (AP in Figure 10b), which were still at the surface during metamorphism of HP ophiolites in Gorgona (GO in Figure 10b). Note that the timing of exhumation of the Tuscan metamorphic units, including the Apuane Alps, was likely overestimated in *Balestrieri et al*. [2011] due to inheritance in zircon grains ascribed to the minimum age peak. Like Calabria, the orogenic wedge of the Northern Apennines was topographically depressed during most of its evolution, and experienced major uplift and erosional exhumation only since early Pliocene times [*Malusà and Balestrieri*, 2012; *Vaselli et al*., 2012].

As shown in section 4, along the Corsica transect, Adria initially acted as the upper plate of the subduction system, until Alpine subduction was choked in late Eocene times and the Alpine orogenic wedge was progressively involved in Adriatic subduction propagating from the south. The Adriatic slab began its translation beneath Corsica as soon as Adria began moving northward, reaching the remnants of the Alpine wedge in Oligocene times [*Malusà et al*., 2015]. The onset of slab rollback-induced extension in the back-arc regions [*Jolivet et al*., 1998; *Faccenna et al*., 2001b], leading to the opening of the Ligurian-Provençal basin and associated Neogene counterclockwise rotation of Corsica-Sardinia, while Adriatic foredeep turbidites were progressively accreted within the Apenninic wedge (Figures 5e and 5f). As a result, two distinct orogenic wedges are now juxtaposed along the Corsica-Northern Apennines transect (Figure 10): (a) to the west, an Alpine orogenic wedge associated with European subduction, which includes HP rocks exhumed from great depth during divergence between upper plate (Adria) and the trench (case (ii) in Figure 1); (b) to the east, an Apenninic wedge associated with Adriatic subduction, which includes progressively younger HP rocks moving toward the foreland and exhumed during rollback of the lower plate (Adria) (case (iii) in Figure 1). During opening of the Tyrrhenian basin, extension east of the Corsica-Sardinia block led to a widespread reactivation of preexisting structures, masking the original relationships between the Alpine and Apenninic orogenic wedges along this transect.

8. Exhumation Styles, Rates, and Geothermal Gradients

As discussed in detail in the sections above, along the Cenozoic subduction zones of the Alps-Apennines system, divergence was controlled by the upper plate to the north, and by the lower plate to the south (Figure 11), leading to different styles of (U)HP rock exhumation along strike. When divergence was controlled by upper plate motion away from the trench, rocks were exhumed from greatest depth at the rear of the accretionary wedge, whereas when divergence was controlled by motion of the lower plate (slab rollback) rocks were exhumed from shallower depth in the frontal part of the wedge, with repeated exhumation pulses progressively younging toward the foreland. These two end-members are cases (ii) and (iii), respectively, in Figure 1.

Major differences between the two end-member scenarios are also observed in exhumation rates and paleogeothermal gradients. Exhumation rates are much higher in the case of upper plate motion away from the trench than in the case of slab rollback, as attested by the different slope of pressure-time exhumation paths (Figure 10b). For upper plate motion away from the trench, divergence actually affected the whole crust synchronously, providing enough space for extremely rapid exhumation of deep-seated rocks up to the surface, with exhumation also promoted by the shallowing of the subducted slab. Such a slab shallowing also prevented any major interaction between the orogenic wedge and the underlying asthenospheric mantle, a scenario that is much more likely in the case of slab rollback (Figure 11). Paleogeothermal gradients during exhumation of the Western Alps eclogites were consequently very low, and can be calculated using the data sets in Figure 7a (and supporting information S1). Our analysis shows that these gradients were dependent on the type of subducted crust at the trench (Figure 11), and did not reach steady state during orogenesis [cf. *Jolivet et al*., 2003; *Malusà et al*., 2006; *Lanari et al*., 2012]. As shown in Figure 11, the eclogites initially experienced geothermal gradients of 5–6°C/km, very close to the forbidden zone (which is

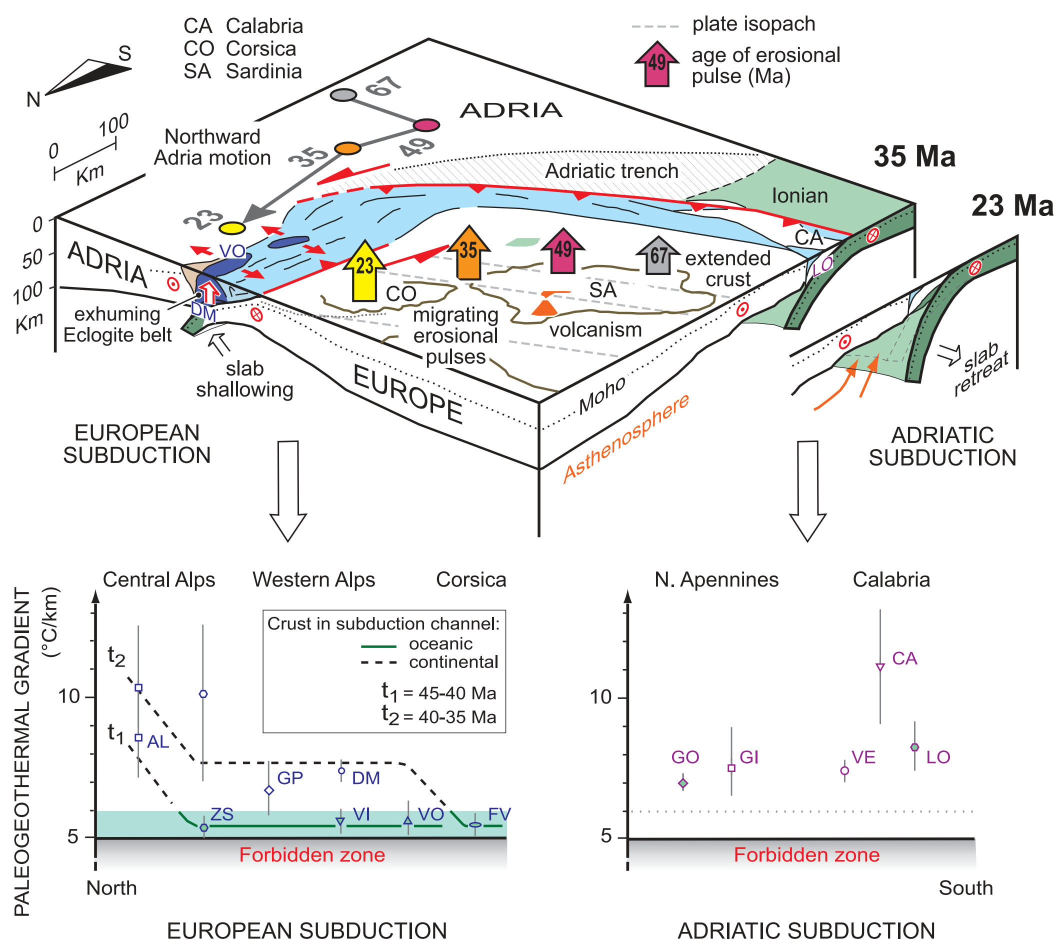

Figure 11. (top) Three-dimensional model showing the relationships between tectonic plates in the late Eocene: on the left side of the model (Corsica transect—CO), the Eclogite belt (dark blue) is exhumed at the rear of the Frontal Alpine wedge (light blue) along the European subduction zone; on the right side of the model, Adriatic continental crust and Mesozoic oceanic crust (green) are actively subducted beneath Sardinia (SA), forming an Apenninic wedge (light blue) also including Calabria (CA). The northward translation of the Adriatic slab beneath Sardinia and Corsica is mirrored by the coeval migration of erosional pulses at the surface(longer arrows = faster rates; Adria trajectory relative to Europe as in Figure 5) [from *Malusà et al*., 2015]. (bottom) Along-strike variation in paleogeothermal gradients along the European and Adriatic subduction zones (based on data in Figure 7 and supporting information S1; VO after *Malatesta et al.* [2012]; acronyms and sample location as in Figures 3 and 4). (left) Gradients in the Western Alps were very close to the forbidden zone (5–6°C/km, time t_1) until subducted crust was exclusively of oceanic type (VI, VO, ZS), and increased to 7–8°C/km when continental crust (DM, GP) was deeply subducted (time t_2). Because subduction was oblique to the northern Tethyan margin, higher gradients characterized first the central Alps (time t_1), and then the Western Alps (time t_2). Gradients in Alpine Corsica remained close to the forbidden zone until final exhumation of HP rocks (FV), because continental crust was not deeply subducted at that segment of the trench. (right) In the Adriatic subduction zone, gradients experienced by the oceanic units (GO, LO) were never close to the forbidden zone, possibly due to the interaction between the accretionary wedge and the rising asthenosphere atop the retreating slab (thin orange arrows in the 23 Ma inset).

defined for geothermal gradients <5°C/km, not expected to be realized on Earth) at least while subducted crust was exclusively of oceanic type (VI, VO, ZS in Figure 11). When continental crust was deeply subducted at the trench (DM, GP in Figure 11), gradients increased to 7–8°C/km, possibly due to a decrease in subduction rates. Because subduction at the Alpine trench was oblique to the European passive margin, the European continental crust was deeply subducted earlier in the central Alps than in the Western Alps. This is in line with the observation that higher paleogeothermal gradients characterized first the central Alps (since 45–40 Ma), and then the Western Alps (since 40–35 Ma). By contrast, paleogeothermal gradients in Alpine Corsica remained close to the forbidden zone until final exhumation of HP units (FV in Figure 11), because continental crust was not deeply subducted at that segment of the trench. As a result, HP rocks of Alpine Corsica are characterized by the widespread and peculiar preservation of lawsonite [e.g., *Caron*, 1994; *Lahondère*, 1996], which is not common elsewhere within the Alpine subduction zone. In the same time interval, paleogeothermal gradients in the Frontal and Cretaceous wedges were on the order of ~20°C/km, and eventually increased to ~30°C/km in the whole belt since 30 Ma.

Exhumation rates above the retreating Adriatic slab were lower than rates inferred for the Western Alps trench. Divergence was in fact more gradual during Adriatic slab rollback, and diachronously affected different levels of the overriding plate (Figure 9b). The higher geothermal gradients—never close to the forbidden zone—that were experienced by the exhuming oceanic units in the Adriatic subduction zone (GO, LO in Figure 11) cannot be explained by differences in the age of the subducted oceanic lithosphere with respect to the Western Alps, but instead possibly reflect the expected thermal response to interaction between the accretionary wedge and the rising asthenosphere atop the retreating slab (Figure 11).

9. Comparison With Synconvergent Exhumation Models

Despite the compelling geologic evidence provided by the stratigraphic record indicating that exhumation took place during episodes of divergence within the plate boundary zone, fixed-boundary synconvergent exhumation models (case (i) in Figure 1), such as the popular channel-flow model [*Beaumont et al*., 2001], are still routinely applied to the Alps [e.g., *Bucher et al*., 2003; *Rosenbaum et al*., 2012]. However, the recently published 2-D numerical models [*Jamieson and Beaumont*, 2013; *Butler et al*., 2013, 2014] provide the opportunity to quantify the amount of detritus expected in sedimentary basins during synconvergent exhumation, and can be also used to test predictions derived using these synconvergent exhumation models with actual constraints from the geologic record (Figure 2).

The model of synconvergent exhumation in Figures 2a–2c is based on the approach described in *Beaumont et al*. [2009], and includes slope-dependent surface erosion that varies spatially according to the local slope of the model surface, with a maximum erosion rate operating on a slope of 45° and scaled down linearly to the local slope of the model [*Butler et al*., 2013]. Using these assumptions, erosion rates during exhumation of HP rocks would be $<$0.8 km/Ma, suggesting that exhumation of HP rocks requires neither rapid erosion, nor lithosphere-scale extension. Accommodation space, in fact, would be provided by the internal extension of the orogenic wedge during ongoing plate convergence [*Jamieson and Beaumont*, 2013; *Butler et al*., 2013].

However, the upward material flux and the progressive reduction in size of the preexisting orogenic wedge accreted against the upper plate (indicated in red in Figures 2a–2c) provides a key for a more reliable and testable estimate of detrital fluxes during exhumation. This is important as numerical models have intrinsic problems dealing with an upper free surface [*Billen*, 2008]. As shown in Figure 2b, using a numerical fixed-boundary synconvergent exhumation model, more than 200,000 km^3 of detritus would be produced in order to exhume the Eclogite belt to the base of the crust, and more than 525,000 km^3 would be produced to exhume the Eclogite belt up to the surface (Figure 2c). However, even using conservative estimates from the model, not including Alpine Corsica and the Lepontine dome, model estimates conflict with the actual geologic evidence that indicates much lower sediment volume (1, in black, in Figure 2d) found in the starved Eocene-Oligocene basins. Moreover, the observed Eocene-Oligocene sediment volume is partly ascribed to intrabasinal carbonate production, not to erosion. The estimated volume of the Oligo-Miocene clastic wedge forming the backbone of the Northern Apennines, and fed by the erosion of the Lepontine dome (Macigno-Modino Fm), is much greater (2, in black, in Figure 2d), but still below 20,000 km^3 [*Di Giulio*, 1999].

Synconvergent models also fail to reproduce other key characteristics of the Western Alps. In spite of the enormous amount of detritus predicted by the models, the size of the exhumed HP volumes (one-tenth of the total orogenic section, i.e., $e = 0.1$ w, see Figure 2c) is much smaller than what is actually observed in the Western Alps ($e = 0.33$ w, see Figure 2f). In addition, synconvergent models predict that rapid exhumation and stacking of (U)HP units at the base of the crust is followed by slower trans-crustal exhumation. Such a prediction is not specific of the model analyzed in Figure 2, but it is also common to other synconvergent exhumation models incorporating a free behavior of the slab [e.g., *Yamato et al*., 2007, 2008; *Burov et al*., 2014]. However, HP rocks of the Western Alps have been rapidly exhumed directly to the Earth's surface in the Eocene, where they were covered by sediments by 32 Ma (black star in Figure 2e). Therefore, pressure-time data for model particles shown in Figure 2e are largely inconsistent with the measured exhumation paths recorded by the Eclogite belt of the Western Alps (shaded areas in Figure 2e). Note however that model particle paths fit quite well the exhumation path of the Lepontine dome, possibly due to the long-lasting trench-normal convergence that characterized the orogenic segment exposed in the central Alps.

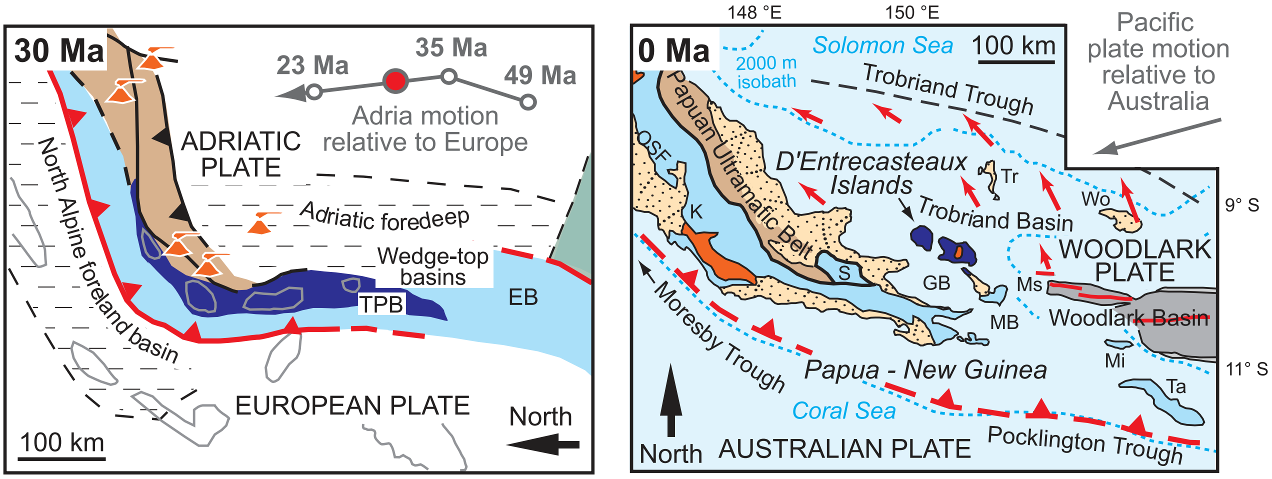

Figure 12. Restoration of the early Oligocene Alps as compared with modern Papua New Guinea. Subduction zones where continental crust was subducted to (U)HP depths, but were no longer active during rock exhumation, are marked in red. (a) Palinspastic map of the Western Alps at 30 Ma, shortly after exhumation of the Eclogite belt, rotated counterclockwise by 90° (same acronyms as in Figure 5). (b) Eastern Papua New Guinea today (simplified after *Baldwin et al.* [2008]). Like in the Western Alps, eclogite units (blue) are exposed behind a lower-pressure accretionary wedge (light blue) [*Webb et al.*, 2014]; GPS data (red arrows) [*Wallace et al.*, 2004, 2014] attest to motion of the upper Woodlark plate away from the Australian plate [*Webb et al.*, 2008]. Differences between the Western Alps and Papua New Guinea are the nature of the upper plate (continental Cretaceous wedge versus oceanic lithosphere) and the changes (i.e., increase) in geothermal gradient as the subduction to rifting transition occurred along the plate boundary in response to the westward propagating Woodlark Basin seafloor spreading system (rift axes in red). Keys: dotted areas, Neogene sediments and volcanic rocks; brown areas, remnants of older orogenic wedges or magmatic arcs; orange areas, Tertiary plutons; grey areas, oceanic crust in the Woodlark Basin. Acronyms: GB, Goodenough Basin; K, Kagi metamorphics; MB, Milne Basin; Mi, Misima Island; Ms, Moresby seamount; OSF, Owen Stanley Fault; S, Suckling-Dayman metabasites; Ta, Tagula Island; Tr, Trobriand Island; Wo, Woodlark Island.

10. Implications for (U)HP Exhumation Mechanisms—Comparisons With a Modern Analog

The tectonic setting of eastern Papua New Guinea (Figure 12) offers a geologically younger (i.e., late Miocene to present) analog for the Western Alps, and in particular, an example of (U)HP exhumation facilitated by removal of the upper plate (case (ii) in Figure 1) [*Webb et al.*, 2008; *Malusà et al.*, 2011a]. The rapidly evolving tectonic evolution of eastern Papua New Guinea is the result of the oblique convergence between the Pacific plate (moving WSW at ~110 mm/yr) and the Australian plate [*DeMets et al.*, 1994]. The region between these two major plates comprises a number of relatively small rotating microplates leading to considerable along-strike variation in relative motion along these rapidly evolving plate boundaries [e.g., *Wallace et al.*, 2004, 2014].

During the Cenozoic, eastern Papua New Guinea occupied the leading northern margin of the Australian plate as it moved northward [*Heine et al.*, 2010]. From 61 to 52 Ma, seafloor spreading in the Coral Sea [*Gaina et al.*, 1999] led to rifting and separation of a continental fragment that was largely comprised of volcaniclastic sediments derived from the Australian continental margin [*Zirakparvar et al.*, 2013]. These continental ribbons were subducted at a north-dipping subduction zone, the remnant of which is now marked by the Pocklington Trough [*Webb et al.*, 2014] (Figure 12b). An accretionary wedge formed as sediments were progressively scraped off the northward subducting Australian plate [*Davies*, 1980, *Davies and Jaques*, 1984] and, by Miocene time, a nascent arc was built upon oceanic lithosphere of the Solomon Sea plate (i.e., Woodlark Island) [*Ashley and Flood*, 1981] with accreted metasediments of the Louisiade Archipelago (e.g., Misima and Tagula Islands) comprising the forearc [*Webb et al.*, 2014]. Subducted sediments and basalts continued to be metamorphosed under high-pressure/temperature conditions, with some reaching mantle depths, and others underplated within the accretionary wedge built beneath the forearc of oceanic island arc(s) [*Baldwin et al.*, 2012]. Peak (U)HP metamorphism [*Baldwin et al.*, 2008] occurred at depths of ~90 km at 7–8 Ma [*Monteleone et al.*, 2007; *Zirakparvar et al.*, 2011; *Baldwin and Das*, 2013].

The reconstructed middle to late Miocene map pattern of exhumed metasedimentary and metabasalt rocks exposed on the Papuan Peninsula, in the D'Entrecasteaux Islands and on the southern rifted margin, and nascent volcanic arc(s) on the northern rifted margin is consistent with the northward subduction polarity. Eclogitic gneisses (dark blue in Figure 12b) of the (U)HP terrane of eastern Papua New Guinea are now exposed on the upper plate side of lower-pressure (prehnite-pumpellyite, greenschist and blueschist) accretionary wedge metasediments (light blue in Figure 12b) [*Worthing and Crawford*, 1996; *Baldwin et al.*, 2012;

Webb et al., 2014]. Eclogitic gneisses form domes that reach elevations of >2.5 km and are flanked by active normal faults [*Davies and Warren*, 1988; *Hill et al*., 1992; *Little et al*., 2007].

Presently, the upper plate to the (U)HP rocks are serpentinized ultramafic and mafic rocks [*Little et al*., 2007; *Baldwin et al*., 2012] inferred to be dismembered ophiolites (i.e., Papuan Ultramafic Belt [*Monteleone et al*., 2001], or Solomon Sea lithosphere [*Gaina and Müller*, 2007]). A carapace shear zone now marks the former subduction thrust that previously separated subducted sediments and basalts from overthrust ophiolitic rocks. The resulting crustal architecture, with relatively low-density (U)HP rocks structurally beneath high-density obducted ophiolites created a density inversion [*Martinez et al*., 2001]. Counterclockwise rotation of the Woodlark microplate due to northward subduction at the New Britain trench farther north led to upper plate removal, allowing rapid exhumation of buoyant, ductiley deformed eclogitic gneisses from beneath mafic and ultramafic upper plate rocks [*Webb et al*., 2008].

Important constraints on the mechanisms for late Miocene to present (U)HP exhumation in eastern Papua New Guinea include: (1) (U)HP rocks were rapidly exhumed [*Baldwin et al*., 2004] from beneath the former thrust along which ophiolite obduction was accommodated [*Davies*, 1980; *Little et al*., 2007], (2) the upper plate (Woodlark Plate) is a rotating microplate [*Webb et al*., 2008] moving counterclockwise away from the Australian Plate [*Wallace et al*., 2004, 2014], (3) buoyancy forces [*Martinez et al*., 2001], likely enhanced by partial melting during exhumation [*Hill et al*., 1995; *Little et al*., 2011; *Gordon et al*., 2012] contributed to exhumation as did (4) late slip on normal faults flanking eclogitic domes [*Davies and Warren*, 1988; *Hill*, 1994; *Little et al*., 2007].

Similarities with the Western Alps include: (1) the similar size and shape of the extensional gneiss domes of the D'Entrecasteaux Islands compared to the size and spacing of the Internal Crystalline Massifs of the Western Alps, (2) similar rates of (U)HP exhumation [*Baldwin et al*., 2004], (3) motion of the upper plate away from the trench, (4) the exhumation of eclogites being facilitated by a density contrast between subducted and accreted material, and the upper plate rocks, and (5) the importance of along-strike variation in the temporal and spatial patterns of rock exhumation, a manifestation of oblique convergence between two major tectonic plates. In the case of eastern Papua, the density contrast is more enhanced due to a density inversion (i.e., lower plate rocks have densities of 2.7–3.0 kg/dm^3, whereas ophiolites of the upper plate have densities of 3.1 kg/dm^3 [*Martinez et al*., 2001].

There are also broad similarities between the Western Alps and eastern Papua New Guinea as regards the stratigraphic record in the adjacent basins surrounding the exhumed (U)HP rocks. Goodenough Basin lies to the south of the D'Entrecasteaux Islands, and the Trobriand Basin lies to the north (Figure 12b). These basins contain a Neogene succession of deep-marine mudrocks and volcaniclastic sandstones, with minor and laterally discontinuous Pliocene conglomerates capped by widespread Quaternary shallow-water carbonates [*Francis et al*., 1987; *Davies and Warren*, 1988]. Most of the detritus in the Goodenough Basin was inferred to be derived from erosion of the emergent D'Entrecasteaux (U)HP domes since the late Miocene, with later Pliocene detritus shed from the Papuan Peninsula when the Dayman Dome was actively exhuming [*Fitz and Mann*, 2013a]. The relatively thin successions of synexhumation sediments (late Miocene and younger) [e.g., *Fitz and Mann*, 2013a] are similar to the late Eocene Epiligurian basins of the Alps that were also largely starved of orogenic detritus during eclogite exhumation [*Francis et al*., 1987; Malusà and *Garzanti*, 2012]. In both the Papuan and Alpine cases, exhumation of (U)HP rocks from depth was therefore not associated with significant erosion, but took place and was largely completed while adjacent sedimentary basins were relatively starved of terrigenous sediments, instead being characterized by the slow accumulation of deep water limestones and mudrocks (cf. Figure 1).

We thus conclude that the sequential stages of subduction and then (U)HP exhumation are distinct, and separated in time from the genesis of topographic relief, which may take place many million years later as documented, for example, by foreland basin stratigraphy throughout the Alpine-Himalayan belt [*Garzanti*, 2008; *Malusà et al*., 2011a]. Synconvergent extension within an accretionary wedge, facilitated by removal of the upper plate (case (ii) in Figure 1) can explain the similarities in crustal thickness to the north and south of the D'Entrecasteaux domes without calling upon crustal flow to move against a gravitational potential [cf., *Little et al*., 2011; *Fitz and Mann*, 2013b]. Exhumation from within an accretionary wedge, at a plate interface where geothermal gradients are low, and prior to westward propagation of the Woodlark Basin seafloor, also allows for the preservation of coesite eclogite during rapid exhumation.

11. Conclusions

Subduction zone kinematics exerts a prominent control on exhumation style, depth, and rate of rock exhumation, as well as on geothermal gradients, preservation of peak pressure assemblages, orogenic-wedge structure, topography development, and detritus production.

Geologic data provide evidence for (U)HP exhumation along the Cenozoic Adria-Europe plate boundary without significant erosion. We propose that exhumation occurred during episodes of divergence within the subduction zone, either controlled by the motion of the upper plate away from the trench (Western Alps) or by the rollback of the lower plate (Calabria).

In the Western Alps, the motion of the upper plate away from the trench allows (U)HP rocks to be exhumed from subcrustal depths at the rear of the accretionary wedge. Exhumation was extremely fast because divergence affected the whole crust synchronously, while geothermal gradients were very close to the forbidden zone (i.e., very low at 5–8°C/km). The slab-rollback mechanism is documented along the Calabria transect to the south, where HP rocks were exhumed from shallower depths and at lower rates during rollback of the Adriatic plate. Along this transect, exhumation took place in the frontal part of the wedge, with repeated exhumation pulses younging toward the foreland. Both of these mechanisms have been active at different times and in different places along the Corsica-Northern Apennines transect, where the western part of the accretionary wedge evolved in the Paleogene during European subduction, and the eastern part evolved in the Neogene during subduction and retreat of the Adriatic plate.

The geologic record preserved in the Western Alps, where (U)HP continental eclogites were quickly exhumed up to the surface to be eventually covered by sediments, is not consistent with numerical models of synconvergent exhumation. Instead, the Western Alps share many similarities with the present-day setting of eastern Papua New Guinea, where the youngest known eclogites on Earth are exposed within a tectonic framework dominated by motion of the upper plate away from the accretionary wedge. Future comparison between the Paleogene Alps and modern Papua New Guinea may thus provide invaluable insights for a better understanding of deep exhumation processes in ancient orogenic belts.

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