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Two-phase orogenic convergence in the external and internal SW Alps

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Abstract: The NW–SE-trending sector of the SW Alps includes the Dora Maira massif where Tertiary eclogites record ultrahigh pressures and rapid exhumation. Along a NE–SW crustal cross-section (Italy–France) compiled pressure–temperature–time data in internal zones are correlated with Tertiary stratigraphy in external zones to reconstruct orogen evolution, revealing a coherent two-phase convergence history. During the first, subduction–accretion phase (Eocene, 55–34 Ma) rapid north–south plate convergence caused the subduction and exhumation of high-pressure and ultrahigh-pressure (UHP) rocks in a steady-state subduction channel. This coincided with the north to NNW migration of an underfilled flexural basin across the European foreland. Nappe stacking within the subduction channel did not create significant relief, implying that primarily subduction forces generated this flexural basin. From 34 Ma onward, the second, collisional phase was characterized by slower NW–SE plate convergence. The internal units of the SW Alps underwent considerable anticlockwise rotation as they became involved in a NW–SE-oriented sinistral transpression zone between the European and Adriatic plates. To the north of the orogen the North Alpine Foreland Basin became overfilled as a result of high sediment supply from increasing orogen relief. In contrast, in SE France active flexure of the European plate appears to have ceased and sedimentation became limited to small thrust-sheet-top basins created by continuing gentle NE–SW shortening. Internal units were exhumed slowly from depths of *c*. 20 km, principally by erosion. In the SW Alps, the transition between these two phases was marked by the rapid subduction and exhumation of the Dora Maira UHP unit. Assuming lithostatic pressure, this unit would have been exhumed from 100 km depth, requiring a rate that exceeds that generated by plate convergence. Therefore, either exhumation was accelerated by additional stresses (locally generated by transpression, slab breakoff or high density contrasts) or, more controversially, the ultrahigh pressure occurred at a considerably shallower depth as a result of local overpressure.

The western Alpine orogen (Fig. 1) was caused by the convergence of the Adriatic microplate and the southward subducting European plate over a period of more than 60 Ma from the Late Cretaceous to the Miocene. Whereas many crustal cross-sections and their restorations have been constructed using the deep seismic profiles of the central and western Alps, few models have been proposed for the SW Alps (the NW–SE-striking arm of the western Alpine arc) where no deep seismic line has yet been shot. This sector includes the Dora Maira massif, where Tertiary eclogites record the highest pressures and most rapid exhumation in the Alps. In addition, the external zones in SE France record a distinct history from that of the central Alps. By integrating our own work with published data, a NE–SW crustal cross-section of the SW Alps has been constructed. We correlate pressure–temperature–time (P–T–t) histories across internal zones with the deformation and foreland basin evolution in external zones. As reconstructions involve considerable rotation and shear, both palaeogeographical maps and cross-sections are used. The trajectories of the internal high-pressure (HP) and ultrahigh-pressure (UHP) units are reconstructed in space and time.

Two phases of exhumation are recognized. It is shown that the subduction and exhumation of HP internal Alpine units are compatible with plate convergence models except for the Dora Maira UHP unit. Reconstruction of the trajectory of this unit during plate convergence demonstrates that forces other than those generated by plate convergence are required if lithostatic pressure gradients are assumed.

Deep structure of the SW Alps

The profile crosses the SW Alps from Savigliano on the Po plain of NW Italy to Digne in SE France (Fig. 2). No deep seismic profile crosses this part of the Alps. Deep structure is therefore constrained only by surface geology and published seismic tomographic models (Solarino *et al*. 1997; Waldhauser *et al*. 1998, 2002; Paul *et al*. 2001; Lippitsch *et al*. 2003). These data constrain the depth of the European Moho and the top and base of the east-dipping Ivrea body. The Ivrea body is a largely buried feature that is defined geophysically as having high density, high magnetic susceptibility and high seismic velocity. It can be traced at depth around the inner curve of the western Alpine arc, where it is estimated to be 10–30 km thick and dipping steeply east (Fig. 1). The roof of its southern

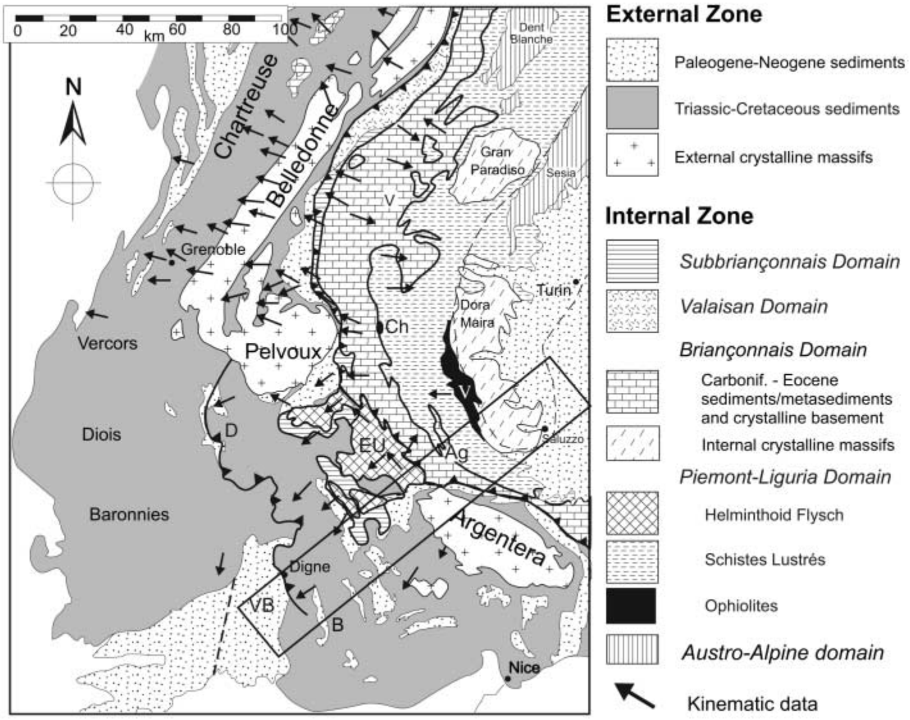


Fig. 1. Geological map of the western Alps showing the location of the cross-section shown in Figure 2. Kinematic data are from Platt *et al*. (1989). The trace of the Ivrea geophysical body is shown by a dashed line (adapted from Schmid & Kissling 2000). VB, Valensole Basin; B, Barrême; Ch, Chenaillet; D, Dévoluy; EU, Embrunais–Ubaye Nappes; Ag, Acceglio.

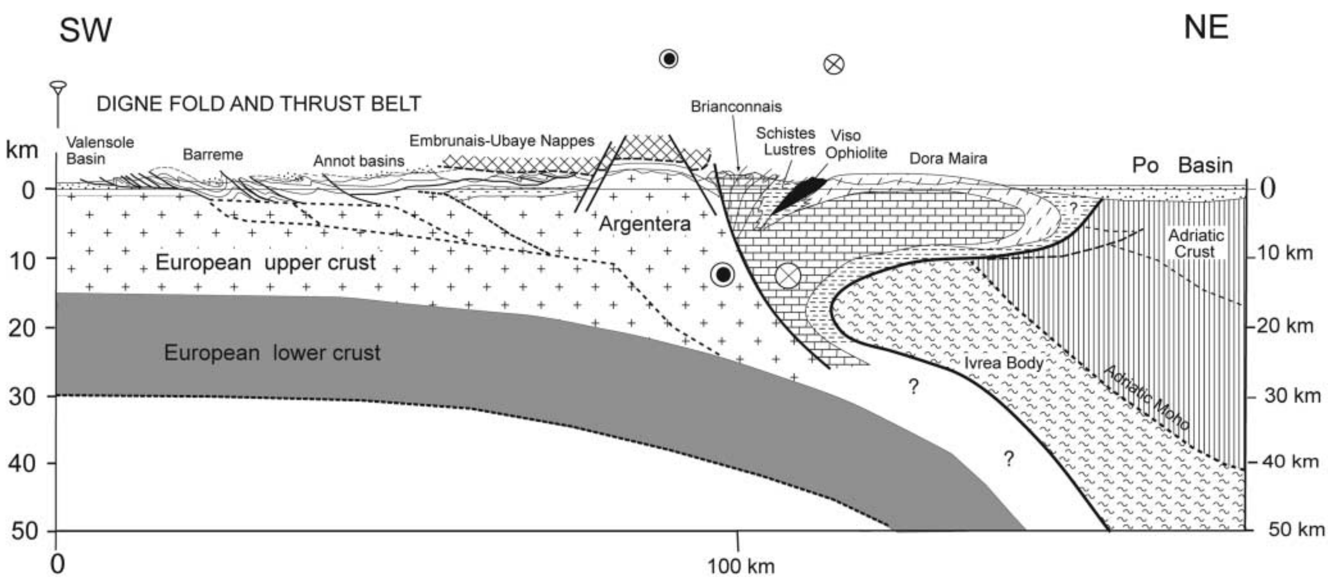


Fig. 2. Synthetic NE–SW crustal cross-section through the study area. Legend as in Figure 1.

termination lies 10 km directly below the southern end of the Dora Maira massif.

The depth of the Adriatic Moho in the study area is poorly defined because the strong signature of the Ivrea body prohibits good tomographic resolution (Waldhauser *et al*. 1998). Ultramafic rocks of lower crustal and upper mantle origin crop out just south of the Insubric Line in the central Alps and are correlated with the Ivrea geophysical body. The Ivrea body is interpreted as part of the Adriatic upper mantle and is shown on our profile as an east-dipping wedge of mantle below the Dora Maira dome. To preserve coherence with crustal models proposed along the ECORS line to the north (e.g. Tardy *et al*. 1999; Schmid & Kissling 2000), the Ivrea body is shown to overlie the subducted European crust (Fig. 2). The contact between the internal Alpine units and the Adriatic crust below the Tertiary Po basin is shown as a SW-dipping thrust overlain by thick Oligocene–Neogene sediments of the Solinaro Basin (Cassano *et al*. 1986; Mosca 2006).

Surface structure of the SW Alps

Internal zone

The internal zone of the SW Alps comprises several tectonic units that, on our transect, stratigraphically belong to three palaeogeographical domains. These domains represent the proximal European passive margin (Briançonnais and Sub-Briançonnais domains) passing eastward through the distal European passive margin into the Ligurian ocean realm (Piemont–Liguria domain) (Stampfli *et al*. 2002). The Austroalpine domain (southern Adriatic plate margin) is not observed in this part of the Alps. Tectonostratigraphic units are defined within these palaeogeographical domains as having a common first-order tectonic and stratigraphic character.

The structure and kinematics of the internal zones in this region are not well constrained, with major differences in data and interpretation between researchers. Four deformation phases are generally recognized, one synchronous with, and three post-dating the HP and UHP metamorphism. Transport directions are towards either the east to NE or the west to SW. A more detailed analysis is considered unfeasaible at present and the reader is referred to Agard *et al*. (2001*a*) for a detailed review of published data and their discrepancies.

The Piemont–Liguria domain is dominated by the Schistes Lustrés (Upper Triassic to Upper Cretaceous), a sequence of monotonous calcschists intercalated on a kilometre to centrimetre scale with marbles, metabasites and ophiolitic slices. The Monviso unit is a 5–6 km thick, west-dipping stack of ophiolitic slices. The tectonostratigraphic units of the Piemont–Liguria domain underwent a polyphase deformation and locally record Alpine eclogitic conditions, overprinted by later more pervasive blueschist and greenschist events (e.g. Schwartz *et al*. 2000*a*).

In the Briançonnais domain, Triassic to Eocene carbonate and clastic sediments overlie a pre-Mesozoic basement of metasediments and gneisses. The Acceglio unit (Fig. 1) records early Alpine eclogite conditions overprinted by blueschist then greenschist conditions (Lefèvre & Michard 1976; Michard 1977; Schwartz *et al*. 2000*b*).

The Dora Maira massif is an elliptical dome-shaped tectonic window of probable Briançonnais rocks appearing from below Piemont–Liguria units (Fig. 1). UHP assemblages are found in a unit 4 km by 10 km and 1 km thick (UHP unit) forming around 3% of the surface area of the SE Dora Maira massif (Chopin 1984; Henry *et al*. 1993). Palaeogeographically, the Dora Maira massif is variably interpreted as either basement on the eastern limit of the Briançonnais domain (European margin; see Debelmas & Lemoine (1970) and Chopin *et al*. (1991) for discussion) or as part of the Adriatic margin (Stampfli *et al*. 2002) or an independent crustal block (Platt 1986). Along its eastern boundary the Dora Maira is unconformably overlain by onlapping Oligocene and Neogene deposits of the Savigliano basin, implying subsidence of up to 5 km since the Oligocene (Mosca 2006).

Based on deep structural models along the ECORS line further north, we speculate that the area between the Dora Maira dome and the Ivrea body is occupied by principally backfolded Briançonnais nappes (Fig. 2).

The internally derived Embrunais–Ubaye nappes include lower tectonic slices of Sub-Briançonnais Triassic–Upper Eocene sediments interleaved with the Autapie nappe of Helminthoid Flysch (Kerckhove 1969) and the upper and largest Parpaillon nappe consisting almost entirely of Helminthoid Flysch. This thick sequence of Upper Cretaceous turbidites is believed to originate from above the internal units. The whole lower Embrunais–Ubaye edifice was emplaced onto the foreland in the early Oligocene, and it was folded there with its substrate (Kerckhove 1969). Emplacement direction is as yet poorly constrained (Merle & Brun 1984; Fry 1989).

Recent workers have documented a composite kinematic history on the contact between external and internal zones (Sue & Tricart 1999; Ceriani *et al*. 2001; Tricart *et al*. 2001), which is referred to here by the non-generic name of Basal Penninic Fault following Ceriani *et al*. (2001). Late Miocene and younger extensional and strike-slip faults cut across the internal and external zones (Tricart *et al*. 2004).

External zone

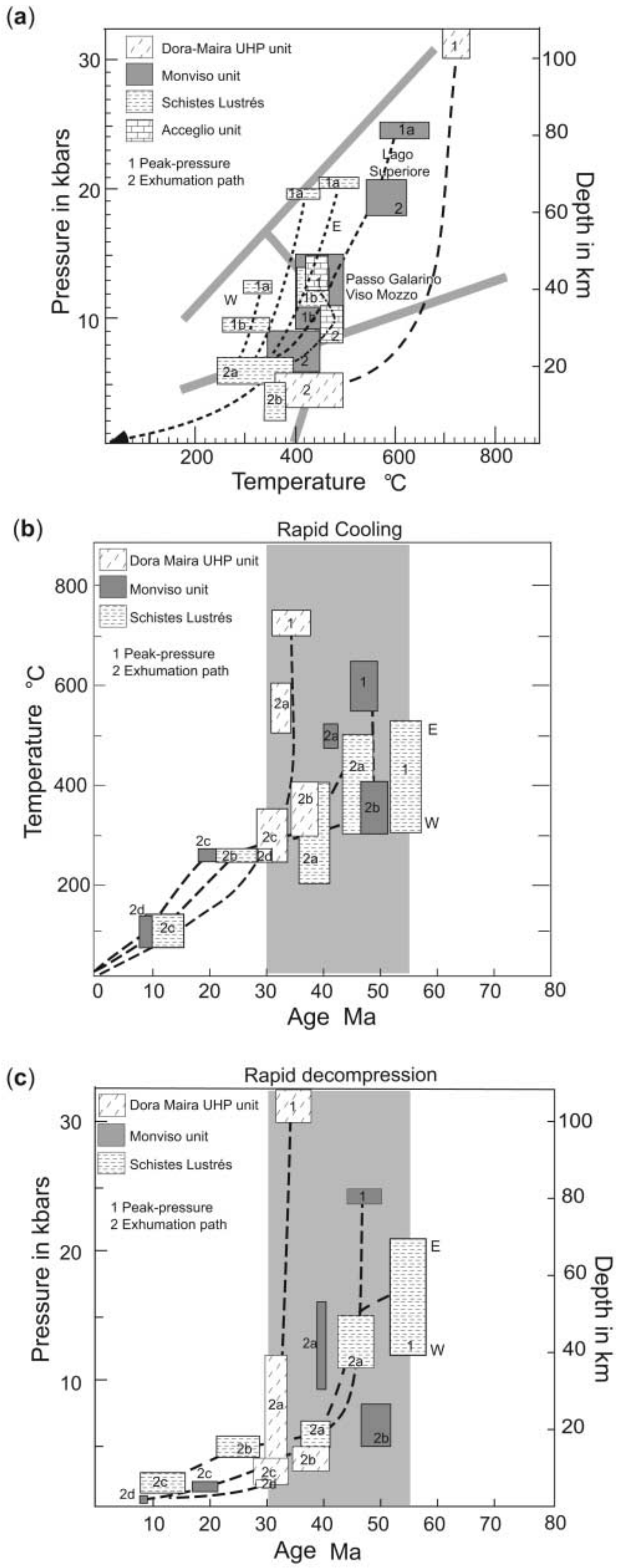
The external fold and thrust belt of SE France comprises the Digne thrust system trending NW–SE and curving southward into the east–west-trending Castellane arc. Our cross-section cuts across the southern Digne thrust system and the northern end of the Argentera basement massif. A Triassic to Cretaceous, mainly carbonate passive margin sequence, up to 4 km thick, overlies Variscan crystalline basement. Remnants of the Eocene–Oligocene foreland basin are preserved as outliers. Sequential section balancing across the area indicates that 21–26 km of basement-involved SW–SSW-directed shortening was accommodated during and after foreland basin development (Ritz 1991; Lickorish & Ford 1998). Active structures (folds and faults) controlled the late Priabonian–early Oligocene Grès d'Annot depocentres (Joseph & Lomas 2004). Mio-Pliocene exhumation of the Argentera crystalline basement massif (Bigot-Cormier *et al*. 2000, 2004) accounts for 10 km of SW shortening and can be linked with final emplacement further west of the Digne thrust sheet over the Mio-Pliocene deposits of the Valensole basin (Fig. 1).

Pressure–temperature–time evolution of the SW metamorphic domain

Since the first report of coesite (Chopin 1984), the western Alps have become the focus of many studies on the exhumation of HP and UHP rocks during plate convergence (e.g. Platt 1986, 1993; Ballèvre *et al*. 1990; Philippot 1990; Chopin *et al*. 1991; Michard *et al*. 1993; Agard *et al*. 2001*a*; Wheeler *et al*. 2001; Reddy *et al*. 2003). The petrological and geochronological data obtained for the main tectonostratigraphic units on the transect (Acceglio, Schistes Lustrés, Monviso and Dora Maira UHP unit) have been given in Figure 3. Data from the Schistes Lustrés are taken from a wider area extending north to the Chenaillet Massif (Fig. 1). The paucity of geochronological data for the Briançonnais unit precluded the reconstruction of its T–t and P–t history. The retrograde P–T paths (Fig. 3a) are based on metamorphic petrology studies referenced in the figure captions. As much as possible, the P–T paths of the various subunits have been reported. The T–t diagrams (Fig. 3b) have been reconstructed from the published data, either by considering the temperature range given by authors (e.g. titanite formation, Rubatto & Hermann 2001; phengite formation, Agard *et al*. 2001*b*) or by assuming approximate closure or retention temperatures chosen to satisfy as much as possible the interpretation of authors (*c*. 350 °C for Ar in white micas, 300 °C in biotite, 500 °C for Rb–Sr in white micas, 250 °C for fission tracks in zircons and 100 °C for fission tracks in apatite). The P–t paths (Fig. 3c) have been constructed by combining the P–T and the T–t diagrams (Fig. 3a and b), except if the age could be directly related to pressure (e.g. pressure estimated from the Si^{4+} content for phengite recrystallization by Agard *et al*. (2001*b*) or from the jadeite content of symplectites by Rubatto & Hermann (2001)). These data allow us to propose a two-phase exhumation history for the internal zones of the SE Alps: a period of subduction and rapid exhumation within the subduction channel during the Eocene, followed by a period of slower exhumation from Early Oligocene onward.

Eocene (55–34 Ma): subduction and rapid exhumation

Petrological studies indicate that peak pressure and temperature conditions were not homogeneous inside each tectonostratigraphic unit. Nevertheless, several workers (e.g. Schwartz *et al*. 2000*a*; Agard *et al*. 2001*a*) have pointed out that there is a general tendancy for peak pressure and temperature to increase from west (300–500 °C, 12–21 kbar in the Schistes Lustrés) to east (700–750 °C, 30 kbar in Dora Maira). Assuming a lithostatic pressure gradient, units were subducted to depths varying between 20 km and 100 km (Fig. 3) but these estimates would be reduced if there were local overpressure conditions (Petrini & Podladchikov 2000).



Although abrupt increases in metamorphic grade may occur across major tectonic contacts (Ballèvre *et al*. 1990; Philippot 1990), similar increases can occur from one subunit to another within individual tectonostratigraphic units, for example in the Monviso unit (Schwartz *et al*. 2000*a*; Agard *et al*. 2001*a*). Furthermore, this compilation shows the following features.

(1) Ages of peak pressure conditions in the Schistes Lustrés and Monviso units (Piemont–Liguria domain) lie within the period 55–45 Ma. Peak pressure in the Schistes Lustrés may be slighty older (55 Ma) than that in the Monviso unit (45–50 Ma).

(2) Although the highest pressure and temperature conditions in the Piemont–Liguria units are recorded by the most easterly Monviso slice (Lago Superiore), the range of pressure and temperature conditions recorded within the Monviso unit overlaps largely with that in the Schistes Lustrés so that the *P–T* gradient is not simply continuous from Schistes Lustrés to Monviso. Instead, these two units appear to have been buried along the same regional thermal gradient (*c*. 8 °C km^{-1} assuming lithostatic pressure, Agard *et al*. 2001*a*). This temperature gradient is geologically significant over the 55–45 Ma period provided that the thermal structure of the subduction channel remained constant over the whole subduction history, and that there were few lateral thermal heterogeneities across the subduction channel. The Schistes Lustrés and Monviso units seem to have sampled, at different times, different parts of a subduction complex characterized by a nearly steady-state thermal structure. This steady-state thermal structure can be generalized for the western Alps as underlined by Fry & Barnicoat (1987), who recognized that all HP Alpine rocks define a common metamorphic gradient of *c*. 8 °C km^{-1} whatever their age. There must have been differential burial, as all units did not experience the same peak pressure conditions (maximum in the Dora Maira UHP unit, no burial of the Helminthoid Flysch).

Fig. 3. *P–T–t* paths. Key to patterns is given in Figure 1. (1) refers to peak-pressure conditions and (2) to the exhumation path. (**a**) *P–T* paths. Dora Maira UHP unit from Chopin *et al*. (1991). Monviso unit peak-pressure (a) from Messiga *et al*. (1999) and Schwartz *et al*. (2000*a*) for Lago Superiore, and (b) from Schwartz *et al*. (2000*a*) for Paso Galarino and Viso Mozzo; exhumation from Schwartz (2002). Schistes Lustrés: (a) west–east transect north of the Chenaillet Massif from Agard *et al*. (2001*a*, *b*) and (b) west–east transect south of the Chenaillet Massif from Schwartz (2002). Acceglio unit from Schwartz *et al*. (2000). (**b**) *T–t* paths. Dora Maira UHP unit peak-pressure age from Tilton *et al*. (1991), Duchêne *et al*. (1997*a*), Gebauer *et al*. (1997) and Rubatto & Hermann (2001); exhumation (a) U–Pb on rutile from Rubatto & Hermann (2001), (b) Ar–Ar on phengite and (c) Ar–Ar on biotite from Monié & Chopin (1991), and (d) fission tracks on zircon from Gebauer *et al*. (1997). Monviso Lago Superiore unit peak-pressure from Duchêne *et al*. (1997*a*) and Rubatto & Hermann (2003); exhumation (a) Rb–Sr on phengite from Cliff *et al*. (1998), (b) Ar–Ar on phengite from Monié & Philippot (1989), (c) fission tracks on zircon and (d) fission tracks on apatite from Schwartz (2002). Schistes Lustrés peak-pressure from Agard *et al*. (2001*a*,*b*); exhumation (a) Ar–Ar phengite from Agard *et al*. (2001*a*,*b*), (b) fission tracks on zircons and (c) fission tracks on apatite from Schwartz (2002). (**c**) *P–t* paths. (See references in (**a**) and (**b**).)

(3) The age of maximum pressure of the Dora Maira UHP unit (35 ± 3 Ma) is much younger than that of the Schistes Lustrés and Monviso units. However, maximum pressures and temperatures also define a gradient of *c*. 8 °C km^{-1}, which may indicate that the thermal structure of the subduction channel remained unchanged up to 35 Ma.

(4) The exhumation paths are all characterized by a continuous cooling, as evidenced by the *T–t* diagrams. Temperatures dropped from their peak to *c*. 300–350 °C (closure temperature for Ar in micas) in less than 10 Ma, which converts to cooling rates of 20–40 °C Ma^{-1}.

(5) *P–t* paths during the Eocene are characterized by steep slopes, and therefore rapid exhumation. The Schistes Lustrés unit was exhumed first, and the Dora Maira UHP unit last, at minimum rates of 1–10 mm a^{-1} assuming a lithostatic pressure gradient. Ar–Ar ages obtained on detrital white micas from Oligocene sediments of the Piemont basin that sample the metamorphic western Alps (Carrapa *et al*. 2003) define two peaks, *c*. 45 Ma and *c*. 38 Ma, and may represent the exhumation of the Piemont–Liguria units first (Schistes Lustrés, Monviso) followed by the Dora Maira UHP unit.

It should be emphasized that in the western Alps, the Dora Maira UHP unit appears to be an end-member in the *P–T–t* paths. The peak metamorphic conditions are the highest, the age of metamorphism is the youngest, and the exhumation is the most rapid. It represents the latest tectonic unit that we now see that benefited from the near steady-state dynamics of the subduction channel. We do not yet know if the history of the Dora Maira UHP unit can be extrapolated to the whole Dora Maira unit.

Oligocene to present day (34–0 Ma): a period of slow exhumation

The period 34–30 Ma (early Oligocene) saw the end of rapid exhumation in the SW Alps. From this time onward, zircon and apatite fission-track data (Schwartz 2002) record cooling at a mean rate of *c*. 10 °C Ma^{-1}, and a slow exhumation (<1 mm a^{-1} assuming a lithostatic pressure gradient) of all units from greenschist-facies conditions. This feature is confirmed by Ar–Ar ages obtained on detrital white micas in the Piemont basin by Carrapa *et al*. (2003). The calculation of cooling rates from the lag-time in the detrital micas records a decrease in the cooling and exhumation rates from 45 °C Ma^{-1} for the oldest sediments (28.5–33.7 Ma) to 10–20 °C Ma^{-1} for the youngest (10–20 Ma). The Ar–Ar ages obtained on detrital white micas are never younger than 30 Ma, which demonstrates that no material has been exhumed from more than 20 km in the last 30 Ma in the western Alps.

The *T–t* data also indicate that the Monviso unit passed through the 250 °C and 100 °C isotherms somewhat later than the Schistes Lustrés. Although it is the youngest HP unit, the Dora Maira UHP unit apparently reached the 250 °C isotherm first at 30 Ma.

Foreland basin evolution

Across the external Alpine chains of SE France, just under 2 km of Palaeogene to Neogene synorogenic sediments are preserved in a series of isolated outliers. These sediments record a diachronous marine transgression that migrated toward the WNW–NW during the mid- to late Eocene (for review see Ford *et al*. 1999; Ford & Lickorish 2004; Joseph & Lomas 2004). Shallow marine carbonates (Calcaires Nummulitiques) are overlain by foraminiferal marls (Marnes à Globigérines) recording a diachronous deepening of the sediment-starved basin. Sediment supply increased during the latest Priabonian and early Rupelian as clastic turbidites (Grès d'Annot) were supplied from the exhuming Sardinia–Corsica block to the south and later by the Maures–Esterels massif (Joseph & Lomas 2004). These turbidites were deposited in SE–NW-oriented synclinal sub-basins (Elliott *et al*. 1985; Du Fornel *et al*. 2004). The area was overthrust by the Embrunais–Ubaye nappes (Kerckhove 1969) toward the end of the Rupelian (around 30 Ma). Sedimentation (mainly fluvial–alluvial, up to 600 m) was then limited to small structurally controlled basins (e.g. Barrême, Dévoluy, Fig. 1) to the west of the Embrunais–Ubaye nappes (Evans & Elliott 1999). From the Burdigalian to the Pliocene more than 2000 m of marine and continental clastic sediments were deposited in the Valensole Basin to the west of the frontal Digne Thrust.

The Tertiary basin history of SE France is correlated with that of the North Alpine Foreland Basin to reconstruct the evolution of the foreland basin around the western Alpine arc (Fig. 4). The map in Figure 4, updated from Ford & Lickorish (2004) using data from Varrone & Clari (2003) and Kempf & Pfiffner (2004),

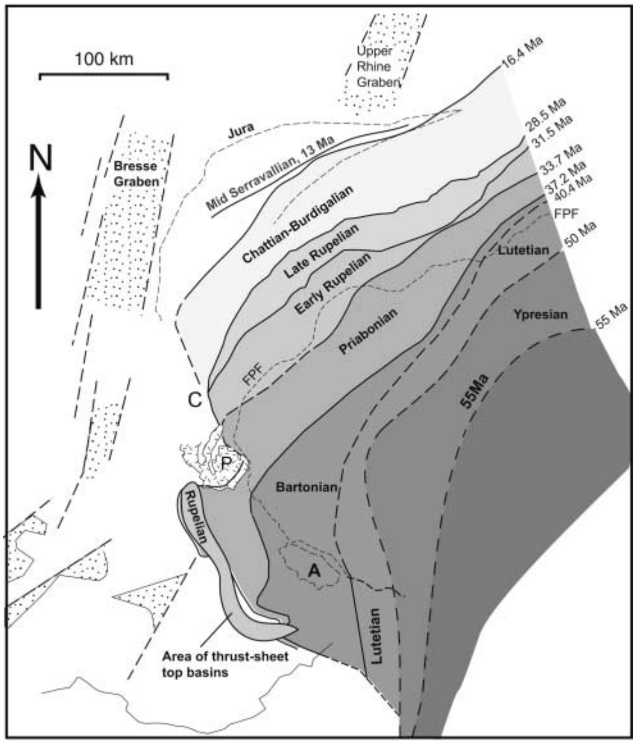


Fig. 4. Synthetic map showing the progressive migration of the outer limit of the western Alpine foreland basin across the European plate from Ypresian to Miocene time. Each dated line represents the outer limit or pinchout of the Alpine foreland basin at the given time. Dashed pinchout lines are more poorly constrained than continuous lines. During the Eocene a single flexural basin migrated to the north and NW. From the early Oligocene to the Miocene a flexural basin migrated to the NW (North Alpine Foreland Basin) only to the north of the orogen closing off to the west at Chambéry (C). In SE France small thrust-sheet-top basins developed during the Rupelian within the outlined area. Revised from Ford & Lickorish (2004) to incorporate data from Varrone & Clari (2003) and Kempf & Pfiffner (2005). Ages are from Gradstein (2004). In the Alpine foreland the Eocene–Oligocene Western European rift system is shown in stipple with dashed lines for normal faults. The Pelvoux massif (P, a palaeogeographical high), the trace of the Frontal Pennine Fault (FPF), the Argentera massif (A), the Jura fold belt and the present-day coastline are shown for reference.

shows the progressive migration of the outer limit of the foreland basin. SW–NE shortening has been restored in SE France and north–south to WNW–ESE shortening has been restored in the central Alps. A major change in basin dynamics can be detected during the Rupelian.

Eocene (55–34 Ma): broad underfilled flexural basin

During the Eocene the northern limit of the underfilled marine basin (Fig. 4) migrated toward the N–NW across the European plate. A general rate of 9–10 mm a^{-1} was estimated by Ford & Lickorish (2004) for the Eocene, and Kempf & Pfiffner (2004) provided a more detailed analysis in the Central Swiss Alps suggesting an initial slow rate (1–2 mm a^{-1}) in the Palaeocene and early Eocene followed by a more rapid migration (20 mm a^{-1}). The pre-Lutetian Alpine foreland basin did not reach the SW external Alps; however, a transgressive Nummulitic series of early Eocene to Ypresian age is preserved in the Solaro basin in northern Corsica (Waters 1990). Therefore, based on sparse data from the central Alps and Corsica, the Early Eocene foreland basin is speculatively represented as a north- to NW-migrating basin around the subduction–accretion orogen. Around 37–34 Ma the orientation of the transgressive coastline of the foreland basin changed from SSE–NNW to ESE–WNW (Kempf & Pfiffner 2004). From Lutetian to Priabonian time (45–34 Ma) the westward closure and migration of the foreland basin was recorded across SE France and can be traced into the central Alps. The deepening-upward stratigraphy of the Nummulitic series (Eocene–Rupelian) is remarkably consistent around the Alpine arc (Sinclair 1997) and can be modelled as a migrating flexural basin (Ford *et al*. 1999). Low sediment supply is interpreted to indicate low relief in the orogen. Flexure of the European plate was therefore not generated by a topographic load but more probably by the negative buoyancy of the subducting plate. Turbidites were supplied to the basin from the late Priabonian onward, indicating increasing relief to the south. These sediments gradually filled the basin to the end of the Rupelian (Joseph & Lomas 2004).

Oligocene–present day (34–0 Ma): end of flexural basin in SE France, overfilled flexural basin to the north of the Alps

After the emplacement of the Embrunais–Ubaye nappes at the end of the Rupelian, no further regional accommodation space was created in SE France (west of the Alps) by lithospheric flexure. Instead, sediment locally accumulated in small tectonically controlled basins (e.g. Barrême).

North of the Alps, however, subsidence and sediment supply increased considerably in the North Alpine Foreland Basin (4 km thickness; Fig. 4). This overfilled basin continued to migrate northward at the same rate until the early Miocene (Aquitanian), when it slowed considerably. This basin closed off to the west at Chambéry (C in Fig. 4). A high sediment supply indicates high orogen relief (Schlunegger *et al*. 1997).

Palaeogeographical reconstructions of the western Alpine orogen

The western Alpine arc developed as a result of the collision of the Adriatic plate with the European plate. Palaeomagnetic data (Dewey *et al*. 1989; Rosenbaum *et al*. 2002*b*) as well as stretching lineations in metamorphic rocks (Choukroune *et al*. 1986; Schmid & Kissling 2000) indicate a change in plate motion direction during the Tertiary from north–south to NW–SE. This change has been dated at 20 Ma by Rosenbaum & Lister (2005) and at 38 Ma by Dewey *et al*. (1989). The motion of the Adriatic plate on our palaeogeographical maps is in accordance with the second hypothesis. Following Schmid & Kissling (2000) we restore the Insubric Line as the northern margin of the rigid Adriatic plate. Palaeomagnetic data from the Briançonnais domain of the SW Alps indicate that significant late Tertiary anticlockwise rotation affected internal tectonic units with respect to stable Europe (Thomas *et al*. 1999; Collombet *et al*. 2002). In contrast, late anticlockwise rotations in the external zones are localized and relatively minor (Aubourg & Chabert-Pelline 1999) and are not considered here. To incorporate these rotational components, internal and external geometries are represented in both cross-section and map view (Figs 5 and 6). Construction of palaeogeographical maps (Fig. 5) involved integration of the data presented above with published plate reconstructions and tectonic models of principally Schmid *et al*. (1996, 1997), Stampfli & Marchant (1997), Collombet *et al*. (2002) and Schmid & Kissling (2000). The Dora Maira unit is shown as a star on cross-sections and maps. The cross-sections in Figure 6 are not restorations of the present-day cross-section (Fig. 2) but instead are intended principally to show the trajectories of internal units through time. Based on Collombet *et al*. (2002), we estimate that the internal zones on our cross-section have rotated through 90° since the early Eocene. Therefore the first three cross-sections (Ypresian, Priabonian and Rupelian) are oriented NW–SE whereas the last (Burdigalian) is oriented NE–SW. Although horizontal distances and depths are respected in the cross-sections and correspond to those on the maps, the geometries of internal nappes is largely speculative as there is little control on present-day deep structure in this area.

Eocene (55–34 Ma)

The Ypresian palaeogeographical map (Fig. 5a) shows the Adriatic plate moving northward with respect to a fixed Europe. The European ocean–continent transition was subducting obliquely below the Adriatic plate. The curved subduction zone passed into a poorly constrained north–south sinistral transform plate boundary to the SW. The subduction complex comprised an accretionary prism, probably of Helminthoid Flysch, overlying the subduction channel. To the north and west the flexural basin was migrating rapidly across the European foreland. The Dora Maira UHP unit was positioned at the southern limit of the European passive margin (Figs 5a and 6a). This model contrasts markedly with that of Stampfli & Marchand (1997) in which the Dora Maira formed part of the Adriatic microplate margin.

The Ypresian cross-section (Fig. 6a), oriented NW–SE, cuts through the transpressive margin on the NW side of the Adriatic plate. Although no evidence of an orogenic lid is preserved today, an early minor Adriatic lid above the subduction channel is drawn to limit the size of the subduction prism. The contact between the Adriatic plate and the subduction channel is shown as a synthetic normal fault (as in the models of Chemenda *et al*. 1996). Slices of Adriatic (Austroalpine) material may have been detached and subducted (but not exhumed to surface) in a similar way to that recorded by the metamorphic evolution of the Sesia and Dent Blanche units (Fig.1) situated just to the north of our cross-section.

During the Eocene, significant convergence is required to subduct all the internal units to HP conditions assuming a lithostatic pressure gradient. Between 50 Ma and 35 Ma (Figs 5a,b and 6a,b), 195 km of north–south convergence is estimated

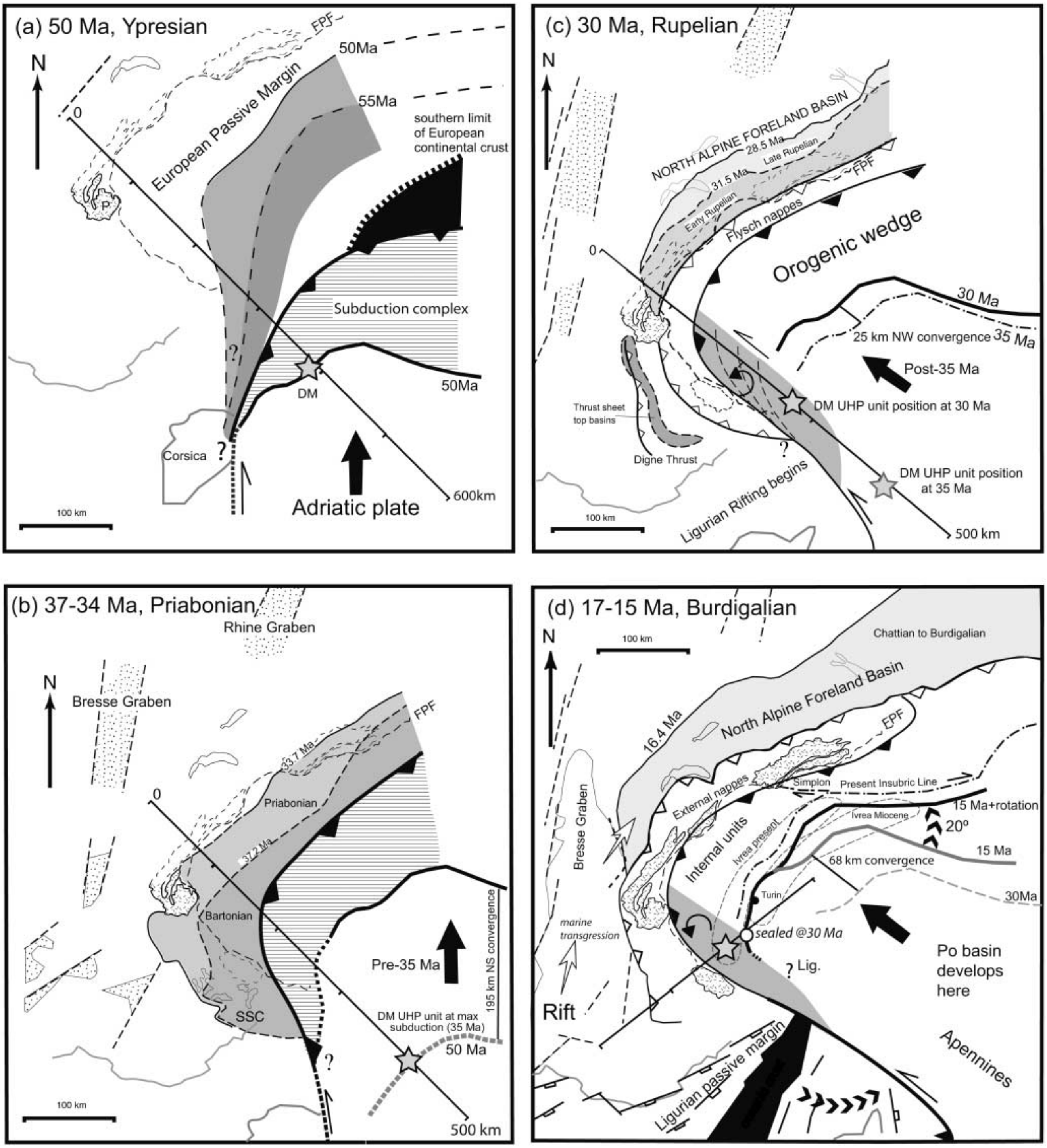


Fig. 5. Palaeogeographical reconstructions of the western Alps during (**a**) Ypresian, (**b**) Priabonian, (**c**) Rupelian and (**d**) Burdigalian times. The corresponding cross-sections are presented in Figure 6. The palaeo-position of the Dora Maira (DM) UHP unit is shown with a star on each map. Oceanic crust is shown in black. Lig., Ligurian Alps. Thick black arrows represent the movement direction of the Adriatic plate with respect to Europe. In (c) and (d) the sinistral plate boundary to the SW of the Adriatic plate links southward (just off the map) to a NW dipping subduction zone that developed from 30 Ma onward to the SE of Corsica and Sardinia (Rosenbaum *et al*. 2002*a*). On the European plate the trace of the Frontal Pennine Fault (FPF) and the external crystalline massifs are shown with fine dashed lines for reference in (**a**)–(**c**). External crystalline massifs are shown as patterned (short lines) in the Miocene when they were being actively exhumed. The Pelvoux massif (P) was a palaeohigh during the Tertiary and thus is patterned in all maps. Lake Geneva (Léman), Lake Neuchâtel and Lake Constance (Bodensee) are shown with continuous lines. The present-day Mediterranean coastline and the outline of Corsica are shown with thick grey lines.

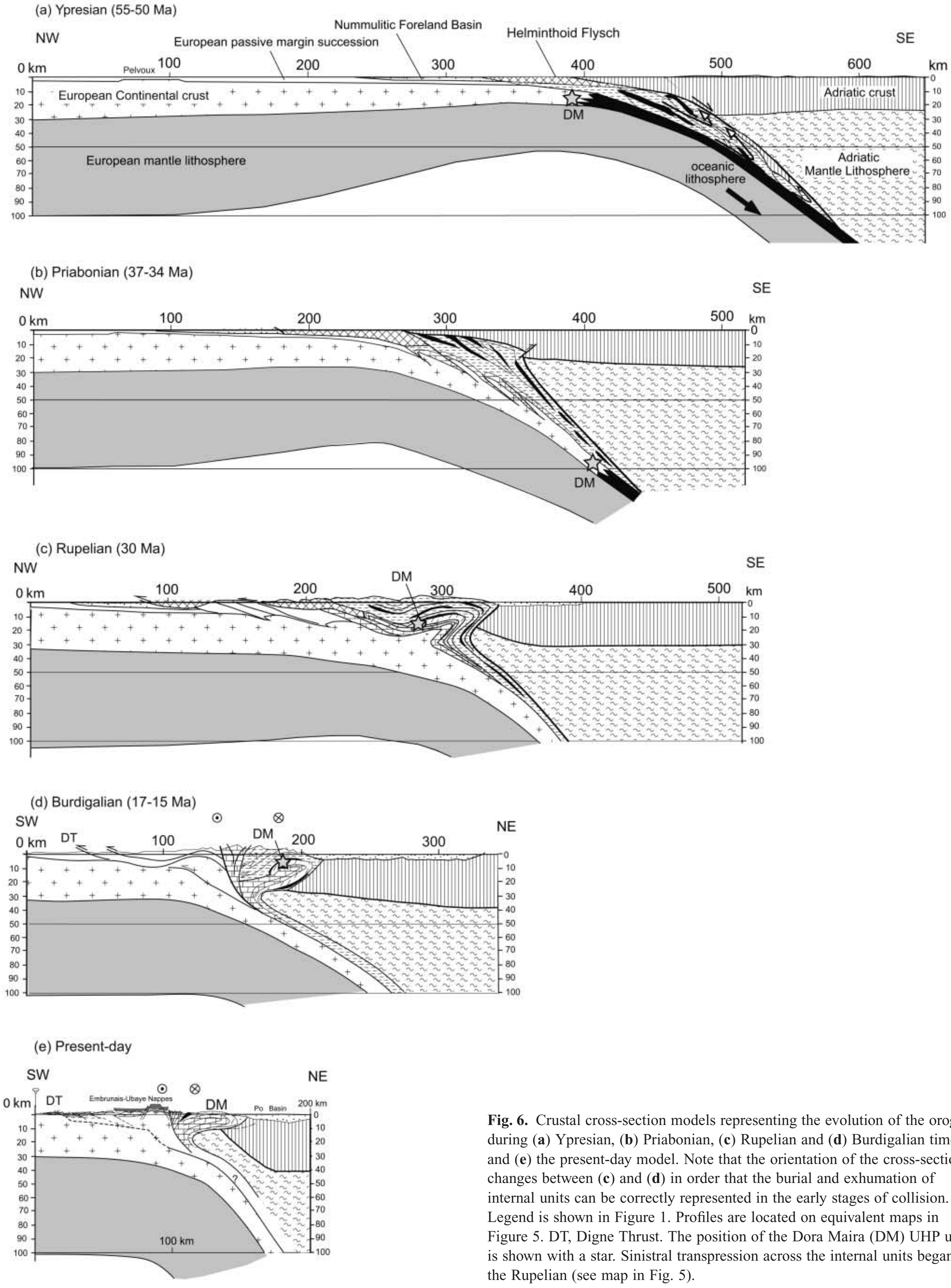


Fig. 6. Crustal cross-section models representing the evolution of the orogen during (**a**) Ypresian, (**b**) Priabonian, (**c**) Rupelian and (**d**) Burdigalian times and (**e**) the present-day model. Note that the orientation of the cross-sections changes between (**c**) and (**d**) in order that the burial and exhumation of internal units can be correctly represented in the early stages of collision. Legend is shown in Figure 1. Profiles are located on equivalent maps in Figure 5. DT, Digne Thrust. The position of the Dora Maira (DM) UHP unit is shown with a star. Sinistral transpression across the internal units began in the Rupelian (see map in Fig. 5).

to have occurred in the central and western Alps (Schmid *et al*. 1996), giving a north–south plate convergence rate of 13 mm a^{-1}. A component of NW–SE convergence of 138 km is therefore estimated along our section line. During the Ypresian, slices of Schistes Lustrés and ophiolites were already subducted to HP conditions (Fig. 3). As the edge of the European passive margin (Dora Maira UHP unit) was just entering the subduction channel, it is reasonable to estimate that it was subducted down to 100 km depth (assuming lithostatic pressure gradients) in 15 Ma (50–35 Ma) in a subduction channel dipping at 36° toward the SE and with a SE-directed subduction component of 11 mm a^{-1}, which is compatible with the north–south plate convergence rate of Schmid *et al*. (1996).

The cross-section for the Priabonian (Fig. 6b) shows the Dora Maira unit at maximum depth whereas the Schistes Lustrés and ophiolitic units were already exhumed to relatively shallow levels in the subduction channel (<30 km). The rocks on our cross-section were progressively approaching the transform plate boundary (see map in Fig. 5b). The Adriatic crust above the subduction zone was being rapidly uplifted and eroded.

The shape and migration of the early foreland basin reflects the northward migration of the Adriatic plate (Fig. 5a). The flexural basin reached SE France in the Lutetian and continued to migrate northward. During the Bartonian and Priabonian, the migration direction changed to NW (Fig. 5b). Further out in the foreland the West European rift system became active in the Priabonian (Séranne 1999).

Oligocene–present day (34–0 Ma)

At around 35 Ma the motion vector of the Adriatic microplate with respect to Europe changed from northward to northwestward (305°; Schmid *et al*. 1996). The SW–NE-striking subduction channel on the western side of Adria thus became a zone of frontal subduction. Plate convergence slowed considerably in the early Oligocene to 5 mm a^{-1} (Schmid *et al*. 1996). We show a reconstruction at 30 Ma to illustrate the 'Dora Maira problem' (Fig. 5c). By this time P–T–t data indicate that the Dora Maira UHP unit had been exhumed to within 10–20 km of the surface (assuming lithostatic pressure). To achieve this, the unit must have moved horizontally 124 km and vertically 90 km within the adopted subduction channel geometry between 35 and 30 Ma. However, NW-directed plate convergence for this period is estimated to have been only 25 km using the rate of 5 mm a^{-1}. Therefore, forces other than plate convergence forces must be evoked to exhume this unit. Figure 6c shows the nappe stack in the late Rupelian, just before emplacement of the Ivrea mantle wedge (Adriatic mantle lithosphere) The cross-section illustrates that between 35 and 30 Ma, the Dora Maira UHP unit was effectively 'injected' into the already exhumed nappe stack near the top of the subduction channel. Based on a similar evolution further north, we propose that the whole nappe stack was backthrust onto the Adriatic crust to create the observed thrust contact. This contact was then sealed by Oligocene deposits and underwent continuous subsidence during the Neogene. From the Oligocene to the present slow and continuous erosion of the HP and UHP units of the internal Alps also supplied sediment with a uniform $^{40}Ar/^{39}Ar$ signature to the Tertiary Piement basin in NW Italy (Barbieri *et al*. 2003; Carrapa *et al*. 2003). Therefore the structure of the western internal nappes changed very little after this time.

Between 30 Ma and 15 Ma, around 68 km of NW convergence occurred in the western and central Alps at a rate of 4.5 mm a^{-1} (Schmid *et al*. 1996). At the same time, the Adriatic plate rotated 20° anticlockwise around an axis close to Turin (Schmid & Kissling 2000; see Collombet *et al*. 2002, for discussion). The Ivrea body is generally located at depth at the front of the Adriatic plate during this late collisional phase (Fig. 5d; e.g. Stampfli & Marchand 1997). During anticlockwise rotation and NW convergence the Ivrea body was wedged below the internal zones of the SW Alps (Fig. 6d). However, no change in the slow exhumation of internal units can be correlated with this deep crustal wedging. Whereas the Insubric Line records dextral displacements during the Oligocene and Miocene (Schmid *et al*. 1989), the contact between the Adriatic crust and internal Alpine units west of Turin was sealed from Oligocene time onward. It is proposed therefore that the 68 km NW convergence was accommodated by sinistral transpression within the internal units between the Dora Maira and the western boundary of the internal zone (shaded areas in Fig. 5c and d).

Discussion

Exhumation processes in the SW Alps

Exhumation processes during the Eocene were due to subduction channel dynamics, which are now well described in numerical, analogue and conceptual models (e.g. Platt 1986, 1993; Fry & Barnicoat 1987; Henry *et al*. 1993; Chemenda *et al*. 1996; Burov *et al*. 2001; Ernst 2001; Gerya *et al*. 2002). Vertical exhumation rates for the Schistes Lustrés and Monviso ophiolitic unit are estimated at around 1–5 mm a^{-1} (Fig. 3), which is compatible with (slower than) the estimated vertical component of the subduction rate (8 mm a^{-1} assuming a convergence rate of 11 mm a^{-1} and a subduction angle of 36°). Rapid exhumation involved complex stacking of tectonic units within the subduction channel with both normal and inverse tectonic contacts. Because maximum P–T conditions vary within a single tectonic unit (e.g. within the Monviso unit or the Schistes Lustrés), and P–T conditions overlap between tectonic units, the size of tectonic slices in the subduction channel was not that of the whole unit but rather that of the smaller subunits observed today (e.g. Monviso is made up of several slices). The Dora Maira UHP unit was the last to be exhumed and at a rate of at least 10 mm a^{-1} (Fig. 3), which is higher than the vertical component of 4 mm a^{-1} assuming a subduction rate of 5 mm a^{-1}. This special case is discussed further below.

Subduction was accompanied by the creation of little or no relief, as is recorded by the underfilled foreland basin. Erosion was therefore not a major exhumation agent during this stage. The absence of a significant topographic load also implies that flexure of the European plate was generated by subduction forces. This may be the case for flexural basins in other orogens that formed early in the collision process.

During the early Oligocene there was a major change in P–T–t paths. The observed decrease in the P–T path slope for each unit (Fig. 3a) is that expected during the exhumation because of the vertical thermal structure of the crust with the gradient increasing upward toward the Earth's surface. But it may also reflect an increase of the thermal gradient through time. The P–t diagram (Fig. 3c) presents a change in slope at around 30 Ma corresponding to a sharp decrease in the vertical component of the exhumation rate. This can be interpreted to mean that either the rock trajectories in the subduction channel had a constant velocity but became more horizontal toward the surface or that the orientation of the trajectories remained constant but their velocity decreased through time, or both (Duchêne *et al*. 1997*b*). It is important to note that only the second scenario would indicate a major change in orogen dynamics at around 30 Ma, which corresponds to changes in the plate movement vector proposed by Schmid & Kissling (2000).

From the Oligocene onward, erosion was probably the principal exhumation process, as present-day erosion rates from the main rivers more or less match required exhumation rates (Milliman & Meade 1983). Sediments eroded from the SW Alps began to accumulate in the Po basin from Oligocene times onward (Barbieri *et al*. 2003; Carrapa *et al*. 2003). This contrasts with the subduction phase, when erosion rates were very low but exhumation rates were 10 times higher. Major relief was created and frontal flexure of the overfilled North Alpine Foreland Basin was generated by subduction, and sedimentary and topographic loads. In contrast to the central Alps, the external zone of the SW Alps did not accommodate significant shortening during this period nor is there a record of active lithospheric flexure. So in the SW Alps, no major tectonic processes need be invoked for post early Oligocene exhumation.

Exhumation of the Dora Maira UHP unit: a special case?

The transition from subduction to collision is marked by the rapid subduction and exhumation of the Dora Maira UHP unit. Exhumation of this unit effectively ceased in the late Oligocene as the eastern margin began to subside and was progressively onlapped by Po Basin sediments. The subduction of Dora Maira at *c*. 35 Ma is in accordance with the reconstruction of plate convergence if we consider it as a distal part of the European margin. However, its exhumation cannot be explained by steady-state subduction channel dynamics because not only exhumation rates but also lateral displacement rates are much higher than those generated by plate convergence. This inconsistency can in part be resolved if the UHP in Dora Maira is considered as due to tectonic overpressure. At present, UHP is proven only in a tectonic slice of 40 km^2 by 1 km thick. It is reasonable to envisage that a local overpressure could develop within such a small volume (Petrini & Podladchikov 2000). Assuming overpressure developed at a maximum depth of 50 km at 35 Ma, the displacement rate during the exhumation is estimated at 16 mm a^{-1}, which is in accordance with the estimated convergence rates of Dewey *et al*. (1989) at *c*. 35–30 Ma. This model could explain why calculated eclogitic P–T conditions are lower in the other Dora Maira subunits. However, the timing of the maximum subduction of these subunits is not constrained. Alternatively, additional mechanisms may have been active during the exhumation to enhance lateral and vertical movements. Slab breakoff could explain the accelerated vertical movement, but not the lateral component. A higher buoyancy for Dora Maira continental rocks compared with other parts of the subduction complex could lead to its movement as an isolated slice relative to surrounding material. Finally, as shown by the palaeogeographical reconstructions (Fig. 5), the Dora Maira UHP unit approached the transpressive western limit of the Adriatic plate at *c*. 35 Ma. The incorporation of the UHP unit into the transpressive zone may have laterally constricted the subduction channel and thus accelerated extrusion of its constituent material.

Regional significance of Eocene–Oligocene transition

In the central Alps, a major change in orogen dynamics occurred in the early Oligocene (34–30 Ma) with emplacement of the Bergell granodiorite, initiation of dextral slip and backthrusting of internal units along the Insubric Line. In the Oligocene, emplacement of the external (Helvetic–Dauphinois) units accommodated over 100 km of NW–WNW-directed shortening associated with thickening of the orogenic wedge and creation of substantial relief. Frontal flexure of the European plate continued to migrate northwestward as recorded by the overfilled North Alpine Foreland Basin.

This major change in Alpine dynamics at the beginning of the Oligocene has been variably attributed to clogging of the subduction system by stacking of tectonic units or by arrival of normal thickness crust into the subduction zone (e.g. Stockmal *et al*. 1986; Schmid *et al*. 1989; Stampfli *et al*. 2002) possibly followed by slab breakoff (von Blanckenburg & Davies 1995; Sinclair 1997). Across the whole Mediterranean region, the early Oligocene was marked by the reorganization of plate movements (Stampfli *et al*. 2002) and it has been suggested that blockage of the Alpine subduction was followed by the creation of a new NNW-dipping subduction zone further south (Rosenbaum *et al*. 2002a).

Conclusions

A major change in Alpine dynamics at the beginning of the Oligocene has been recognized in foreland and internal zone evolution of the SW Alps.

Eocene subduction–accretion phase (50–34 Ma)

While the Adriatic plate moved northward with respect to a fixed Europe at a rate of 13 mm a^{-1}, the European ocean–continent transition in SW Alps was subducting obliquely below the Adriatic plate. The sedimentary record and the P–T–t path of metamorphic rocks indicate low relief and rapid exhumation of metamorphic rocks derived from oceanic crust and overlying sediments. Exhumation of HP and UHP rocks is not controlled by erosion at this stage but is best explained by steady-state subduction channel dynamics.

Oligocene to present-day collision phase (34–0 Ma)

The motion of the Adriatic microplate with respect to Europe changed from north-directed to NW-directed (Schmid *et al*. 1996). The internal SW Alps became accordingly a zone of sinistral transpression pinched between the Adriatic and European plates. Plate convergence slowed considerably to 5 mm a^{-1}. This period corresponds to high orogen relief and high erosion rates, as indicated by stratigraphy in the North Alpine Foreland Basin. Erosion can account for the slow exhumation rates observed in the internal zone at this stage.

The transition between these two phases is marked by the subduction and exhumation of the UHP unit of Dora Maira. If the maximum subduction depth of this unit was 100 km (which assumes purely lithostatic pressure), the required vertical and horizontal exhumation rates exceed those generated by plate motion. This discrepancy may be resolved by evoking additional stresses, which may have been generated by increasing lateral constriction within the transpressive plate boundary, slab breakoff or high density constrasts within the subduction channel, or any combination of these. Alternatively, Dora Maira was never subducted to 100 km but the ultrahigh pressure was generated by significant local overpressure.

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