Metamorphism of metasediments at the scale of an orogen: a key to the Tertiary geodynamic evolution of the Alps*

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Abstract: Major discoveries in metamorphic petrology, as well as other geological disciplines, have been made in the Alps. The regional distribution of Late Cretaceous–Tertiary metamorphic conditions, documented in post-Hercynian metasediments across the entire Alpine belt from Corsica–Tuscany in the west to Vienna in the east, is presented in this paper. In view of the uneven distribution of information, we concentrate on type and grade of metamorphism; and we elected to distinguish between metamorphic paths where either pressure and temperature peaked simultaneously, or where the maximum temperature was reached at lower pressures, after a significant temperature increase on the decompression path.

The results show which types of process caused the main metamorphic imprint: a subduction process in the western Alps, a collision process in the central Alps, and complex metamorphic structures in the eastern Alps, owing to a complex geodynamic and metamorphic history involving the succession of the two types of process. The western Alps clearly show a relatively simple picture, with an internal (high-pressure dominated) part thrust over an external greenschist to low-grade domain, although both metamorphic domains are structurally very complex. Such a metamorphic pattern is generally produced by subduction followed by exhumation along a cool decompression path. In contrast, the central Alps document conditions typical of subduction (and partial accretion), followed by an intensely evolved collision process, often resulting in a heating event during the decompression path of the early-subducted units. Subduction-related relics and (collisional/decompressional) heating phenomena in different tectonic edifices characterize the Tertiary evolution of the Eastern Alps. The Tuscan and Corsica terrains show two different kinds of evolution, with Corsica resembling the western Alps, whereas the metamorphic history in the Tuscan domain is complex owing to the late evolution of the Apennines. This study confirms that careful analysis of the metamorphic evolution of metasediments at the scale of an entire orogen may change the geodynamic interpretation of mountain belts.

After more than a century of investigations, the Alps still represent an outstanding natural laboratory for the study of geodynamic processes linked to the evolution of mountain belts in general. The integration of regional geology and metamorphic evolution provides highly needed constraints for increasingly complex quantitative models (e.g. Escher & Beaumont 1996; Henry *et al.* 1997; Pfiffner *et al.* 2000).

Major discoveries in metamorphic petrology, as well as other geological disciplines, have been and are still made in the Alps. For example, eclogites were described for the first time in the eastern Alps (Koralpe, Saualpe massifs) by Haüy (1822). More recently, the discovery of coesite in the Dora Maira unit (Chopin 1984, 1987) proved that continental crust went into subduction, contrary to a still widely held opinion, and returned from

*This paper is dedicated to Martin Burkhard who tragically died during work in the Alps.

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great depths. Many others, occasionally less spectacular yet important, petrological discoveries, were also made in the Alps. For instance, studies of metapelites in the Alps starting at the beginning of the 1970s, revealed a specific mineralogy reflecting high-pressure conditions. The most emblematic minerals found in such rocks are ferro- and magnesiocarpholites (Goffé *et al.* 1973). Besides such discoveries, many holistic attempts have been made to assess the dynamics of this orogen. Niggli & Niggli (1965) applied Barrow's concept to the central Alps and presented a mineral distribution map with mineral isograds reflecting a Lepontine high-temperature event. Zwart (1973) and Zwart *et al.* (1978) compiled mineral distributions at the scale of the orogen, using the facies concept and available age data in the Alps and elsewhere.

Based on such mineralogical work, Ernst (1971) was able to use the plate tectonic concept for proposing a first modern model for the evolution of the Alps. Such ideas developed further on the basis of work such as that of Dal Piaz *et al.* (1972), Dal Piaz (1974*a*, *b*) and Hunziker (1974), just to name a few. Frey (1969), as well as Trommsdorff (1966), started to investigate metamorphism in isochemical systems provided by shales and siliceous carbonates, respectively. This allowed for quantitatively constraining the Cenozoic temperature evolution in the central Alps. Frey *et al.* (1999) compiled all available information on the peak temperature distribution, and used the occurrence of eclogites to display the dynamics of the Alpine evolution. Previous works of this kind led to the compilation of a new map showing the metamorphic structure of the Alps (Oberhänsli *et al.* 2004). This new map was also based on: (1) new tectonic concepts and maps (Schmid *et al.* 2004); (2) a wealth of new radiogenic age data (for references see e.g. Handy & Oberhänsli 2004, and Berger & Bousquet 2008); and (3) an extension of the facies concept based on mafic to metapelitic rock compositions.

In the Alps, many areas are devoid of index minerals classically observed in mafic and quartzofeldspathic rocks systems, allowing a direct comparison to be made. Petrological investigation on metasediments greatly helps to constrain geodynamic evolution of such areas (see Bousquet 2008). One tool to understand such problems better at the orogen scale is maps (Niggli & Niggli 1965; Niggli 1970; Frey *et al.* 1999; Oberhänsli *et al.* 2004). This study combines these different sources of information: presenting metamorphism in maps and combining this with metamorphic evolution data. This provides insights into the geodynamics of metasediments inside the orogen. The metamorphism of metasediments can be subdivided into general geodynamic groups: (1) pressure-dominated metamorphism; (2) temperature-dominated metamorphism at intermediate pressures (Barrovian metamorphism), which is often referenced in the literature as HT metamorphism; and (3) contact metamorphic aureoles which are temperature-dominated metamorphism at low pressures. The latter type will be excluded from this contribution because it is only of minor importance in the Alps.

This paper reviews existing data and presents ongoing work in an attempt to integrate metamorphic studies and Late Cretaceous–Tertiary geodynamic concepts in the Alps. We will illustrate how mineral data obtained from metasediments may constrain the geodynamic evolution of mountain belts in general.

Metamorphic mineralogy of metasediments

In contrast to mafic complexes or meta-igneous rocks, metasediments commonly crop out continuously over very large areas in many mountain belts, such as the Alps (Fig. 1). Since these metasediments cover large areas, this allows to simultaneously observe their structural and metamorphic evolution, and thus to decipher the geodynamic frame. However, since Barrow (1893, 1912) and Eskola (1929), the definition of metamorphic facies, as well as petrographic work on metamorphic rocks, was mainly focused on mafic systems (Evans 1990; Frey *et al.* 1991; Carswell 1990).

Detailed studies on pelitic systems (Yardley 1989; Koons & Thompson 1985; Spear 1993; McDade & Harley 2001) are only available for medium- to high-temperature metamorphic conditions. Metamorphic studies addressing low-temperature conditions extended methods taken from studies on diagenesis or anchimetamorphism, such as illite crystallinity, vitrinite reflectance or clay mineralogy (Frey & Robinson 1999) which lack good possibilities of pressure and temperature calibration. Spectacular improvements on the knowledge of mountain belt evolution based on the study of metasediments could only be made starting with the discovery of coesite in metasediments (Chopin 1984) and other work on Ultra High Pressure rock systems (UHP) in general (Coleman & Wang 1995; Chopin & Sobolev 1995; Massonne & O'Brien 2003).

Petrogenetic grids

Classical index minerals, such as pumpellyite, glaucophane or jadeite, observed in mafic and quartzofeldspathic rocks systems, are unfortunately rarely

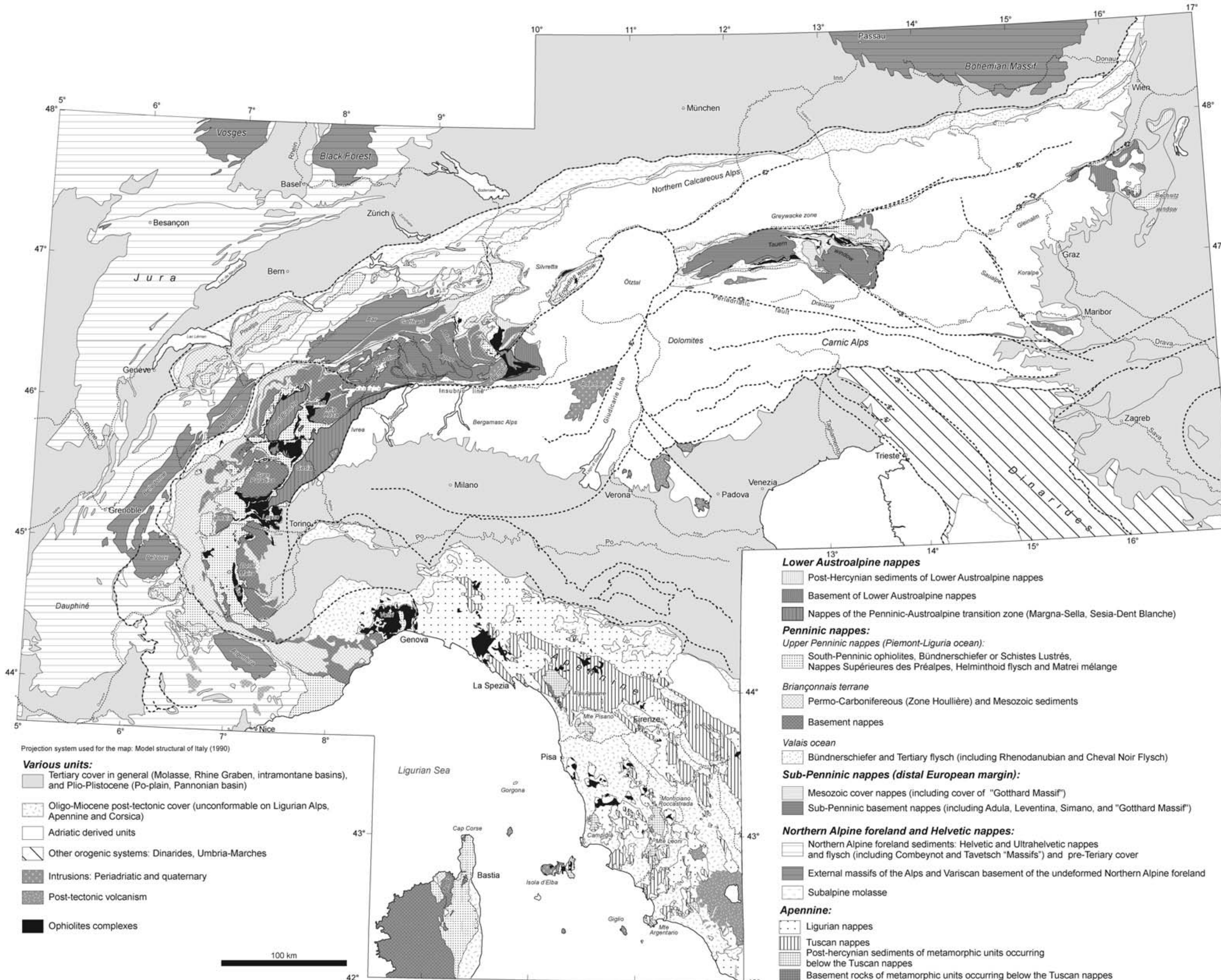


Fig. 1. Structural units of the Alps involved and metamorphosed during the Late Cretaceous–Tertiary orogeny from Vienna (Austria) to Corsica and Tuscany. The distribution of metasediments, ophiolites and basement rocks is not homogeneous over the whole Alpine edifice. In the west, in Tuscany, Corsica and western Alps, the belt is mainly built of post-Hercynian metasediments from oceanic (mainly Piemont–Liguria) or continental (Briançonnais cover and European platform) origin. Several ophiolitic complexes are associated with oceanic sediments (Zermatt, Lanzo, Viso, Voltri). Scarce fragments of basement rocks occur as structural domes (Monte Rosa, Gran Paradiso, Ambin, Dora Maira, Tenda) in the internal parts or are located at the external border of the belt (Mont Blanc, Belledonne, Pelvoux, Argentera). From the Simplon line in the central Alps to the eastern Alps, mainly basement rocks have been imbricated into the orogenic pile (Lepontine dome, Tauern Window) except for the Engadine window. Upper Austroalpine units are not detailed on the map. Map modified after Froitzheim *et al.* (1996) and Schmid *et al.* (2004) with additional data from Bigi *et al.* (1990) and Koller Höck (1987).

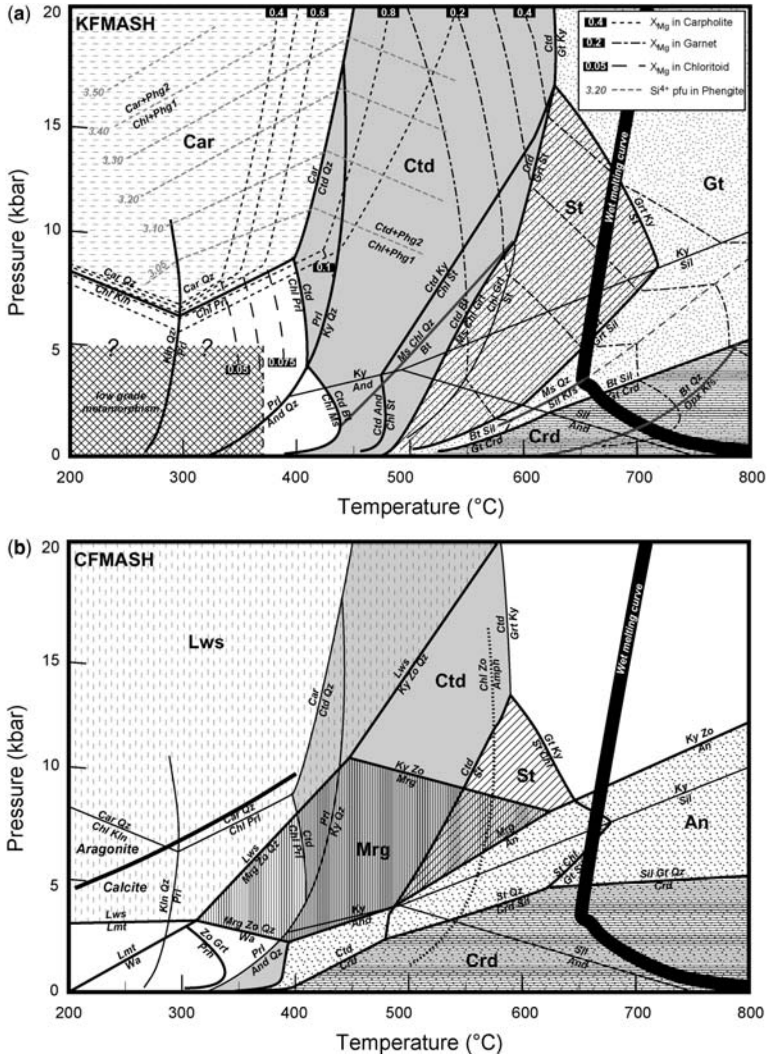


Fig. 2. Petrogenetic grids for metapelites for a temperature range from 200 to 800 °C. (**a**) In the KFMASH (K_2O–FeO–MgO–Al_2O_3–SiO_2–H_2O) system, the grid is strongly temperature-controlled. The appearance of assemblages, from (Fe, Mg)-carpholite assemblage at HP or from chlorite–pyrophyllite assemblage delimits the low-temperature domain from the middle temperature one at around 400 °C. The exact temperature limit depends on rock and mineral chemistry. At higher temperature conditions, the breakdown of chloritoid into garnet or staurolite indicates the transition towards high-temperature domains between 500 and 600 °C depending on pressure conditions as well as on rock and mineral chemistry. (**b**) In the CFMASH (CaO–FeO–MgO–Al_2O_3–SiO_2–H_2O) system, the temperature control is less important. While under LT conditions, lawsonite is the main stable mineral, sometimes coexisting with (Fe, Mg)-carpholite; at middle and HT conditions, margarite and staurolite stability fields are pressure-dependent. We note a large cordierite-stability field in the CFMASH system.

Diagrams drawn from field experience and theoretical studies after Spear & Cheney (1989), Wang & Spear (1991), Vidal *et al.* (1992), Oberhänsli *et al.* (1995), Bousquet *et al*. (2002), Proyer (2003), wei *et al*. (2004), Wei & Powell (2004), Wei & Holland (2003), Chatterjee (1976), Frey & Niggli (1972), Zeh (2001), Pattison *et al.* (2002), McDade & Harley (2001), Kohn & Spear (1993), Hébert & Ballèvre (1993) as well as own calculation using the Theriak-Domino software (De Capitani & Brown 1987, De Capitani (1994) using Berman database (1988) completed by recent thermodynamic data: Mg-chloritoid data of B. Patrick (listed in Goffé & Bousquet 1997), Fe-chloritoid data of Vidal *et al.* (1994), chlorite data of Vidal *et al.* (2001), and alumino-celadonite data from Massonne & Szpurka (1997). Mineral abbreviations are from Bucher & Frey (1994) except for (Fe, Mg)-carpholite (Car).

observed in Alpine metasediments. Nevertheless, metasediments have highly variable chemical and mineralogical compositions that represent an important geothermobarometric potential. Figure 2 shows petrogenetic grids for the KFMASH and CFMASH subsystems that integrate field observations, experimental data and thermodynamic modelling using an internally consistent database. This new kind of compilation covers a large P–T space, extending from low to high pressure (0–2 GPa) as well as from low to high temperature (200–800 °C).

Mineral assemblage containing ferro-magnesio-carpholite with phengite, chlorite and quartz is one of the most emblematic mineral assemblages of metasediments in the KFMASH system (De Roever 1951; Goffé *et al.* 1973; Chopin & Schreyer 1983; Goffé & Chopin 1986; Rimmelé *et al.* 2003). It is encountered in various rock types, such as aluminium-rich metapelites, quartzites, marbles and albite-free pelitic schists in which it is abundant, often in veins. Textural and mineralogical observations in these rocks reveal that at low temperatures the main equilibrium reactions of ferro- and magnesio-carpholite involve quartz, kaolinite, pyrophyllite, kyanite, chlorite, chloritoid and phengite (Fig. 2a). At high temperatures, large P–T fields are dominated by an assemblage containing staurolite, biotite and garnet (Spear & Cheney 1989). Fe–Mg variations in mineral composition, as a function of P and T (Goffé 1982; Spear & Selverstone 1983; Vidal *et al.* 1992; Theye *et al.* l992), as well as Si isopleths in phengite (Massone & Schreyer 1987; Oberhänsli *et al.* 1995; Massone & Szpurka 1997; Bousquet *et al.* 2002) allow for relatively precise P–T estimates (Vidal *et al.* 2001; Parra *et al.* 2002*a*, *b*; Rimmelé *et al.* 2005) for some metapelitic compositions.

In the CFMASH system, for comparison, there is less resolution at low-temperature conditions. In carbonaceous systems, the stability field of the index mineral lawsonite covers the whole low-grade space, including the stability field of carpholite and the aragonite–calcite transition. While the staurolite field is substantially smaller in the CFMASH system, as compared to the KFMASH system, margarite and zoisite are characteristic of medium P and T conditions.

Oberhänsli *et al.* (2004) proposed a new type of metamorphic facies grid that better integrated field observations into models of the geodynamic. This facies grid also took into account the importance of metasediments, which is less clear in traditional grids. The proposed grid also involved more subdivisions, which are based on the understanding of the metasediments. Based on these compilations, a revised version of this tool is presented in Figure 3, and it will be used in this paper.

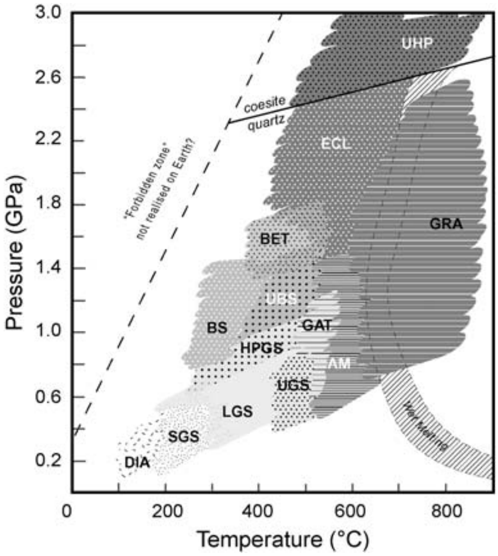


Fig. 3. Metamorphic facies diagram for metapelites and metabasites (modified after Oberhänsli *et al.* 2004). This diagram has been used for Figures 6 and 7. For abbreviations, see Table 2. This diagram is in good agreement with previous published facies diagrams (e.g. Yardley 1989; Spear 1993; Bousquet *et al.*1997).

Ambiguity of some mineral assemblages in the Alps

While some parageneses unambiguously grow only within a certain geodynamic context (Table 1a), other mineral assemblages commonly occur over a large field of P–T conditions and may evolve in diverse geodynamic contexts. Examples of unambiguous mineral assemblages containing lawsonite and carpholite only form under low-temperature/high-pressure conditions, typical for subduction processes; mineral assemblages containing staurolite and andalusite are typical high-temperature phases occurring during collision processes (i.e. Barrovian-type metamorphism).

On the other hand, recurrent minerals such as chloritoid, zoisite, kyanite and garnet may form at different P–T conditions. This hampers their use for an interpretation of the geodynamic setting. Chloritoid–phengite assemblage, for example, can be produced in different geodynamic settings. Moreover, it may occur in tectonic units in close spacial juxtaposition although these units formed in different geodynamic scenarios (Oberhänsli *et al.* 2003). Figure 4 clearly illustrates that two P–T paths may lead to different mineral reactions that produce chloritoid–phengite–chlorite mineral assemblages. The P–T path along a cold geotherm leads to the formation of chloritoid–phengite–chlorite as a result of the breakdown

Table 1. *Mineralogical description of the metamorphic facies presented in Figure 3 for basic rocks as well as for meta-pelitic rocks*

Facies Name	Abb.	Basic rocks	Metapelites
diagenesis/sub anchizone	DIA	zeolite	illite–kaolinite
sub greenschist	SGS	laumontite–prehnite–pumpellyite	illite
lower greenschist	LGS	albite–chlorite	pyrophyllite–chlorite $\pm$ chloritoid
upper greenschist	UGS	actinolite–epidote–chlorite	biotite–chlorite–kyanite $\pm$ chloritoid
high–pressure greenschist	HPGS	albite–lawsonite–chlorite $\pm$ crossite	lawsonite–chlorite $\pm$ chloritoid $\pm$ kyanite
greenschist–amphibolite transition	GAT	albite–epidote–amphibole	biotite–garnet–chloritoid or phengite–chloritoid–kyanite
amphibolite	AM	plagioclase–hornblende– garnet	biotite–garnet–staurolite–phengite $\pm$ kyanite
blueschist	BS	glaucophane–lawsonite	carpholite–phengite $\pm$ pyrophyllite
upper blueschist	UBS	glaucophane–epidote–garnet	chloritoid–phengite $\pm$ garnet
blueschist–eclogite transition	BET	glaucophane–zoisite–garnet $\pm$ clinopyroxene	garnet–Mg–rich chloritoid–phengite
eclogite	ECL	garnet–omphacite–zoisite– quartz $\pm$ amphibole $\pm$ phengite	garnet–Mg–rich chloritoid–kyanite or garnet–lawsonite
ultrahigh–pressure	UHP	garnet–omphacite–kyanite $\pm$ phengite	coesite or Mg–rich chloritoid–talc–phengite
granulite	GRA	plagioclase–clinopyroxene (augite)–orthopyroxene (hypersthene) $\pm$ garnet $\pm$ olivine $\pm$ spinel	clinopyroxene (diopside)–orthopyroxene (enstatite)–K–feldspath $\pm$ garnet $\pm$ corderite $\pm$ sapphirine

of Fe–Mg carpholite (Chopin & Schreyer 1983) while under higher geothermal gradients this assemblage can also form by the breakdown of pyrophyllite (Frey & Wieland 1975).

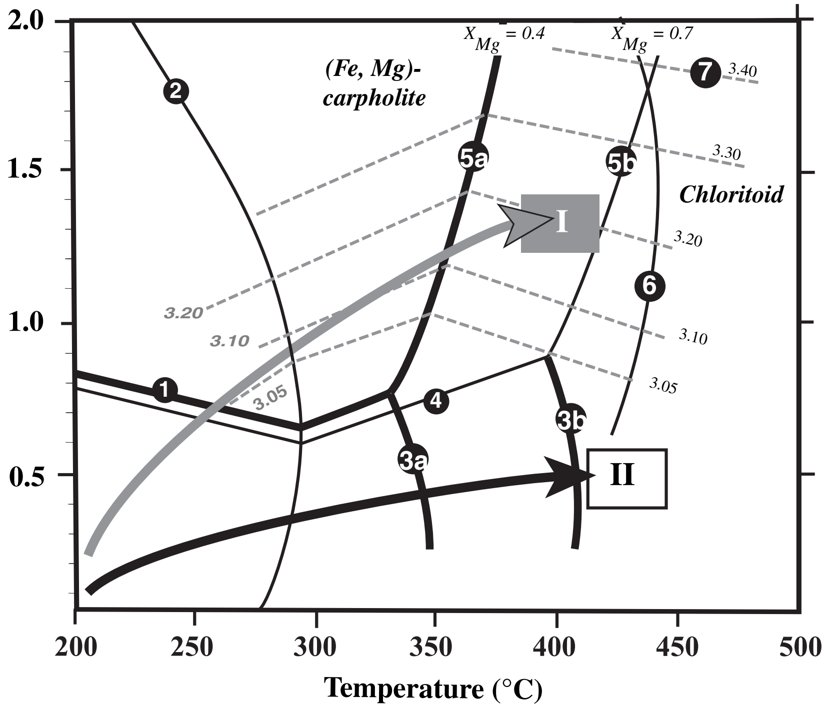
The high-pressure alumosilicate polymorph, kyanite, is particularly difficult to interpret as an indicator of geodynamic processes. It may occur in UHP associations such as the Dora Maira unit, as well as in temperature-dominated areas such as the Lepontine dome. It indicates a subduction-type low geothermal gradient in the first, but a high collision-related geotherm in the latter case.

Ambiguity of some metamorphic facies

Assignment of a metamorphic rock to a metamorphic facies is based on its mineralogy. In the best case, a rock might undergo a simple metamorphic evolution in a distinct geodynamic setting, leading to a peak metamorphic paragenesis (simultaneous P and T peaks) possibly followed by later retrogression (Fig. 5a). However, a metamorphic pressure peak related to one geodynamical scenario may also have been overprinted by a thermal peak that resulted from a second and different geodynamic scenario (Fig. 5b). Hence, in such a case metamorphic facies is ambiguous in that it is difficult to distinguish between continuous and discontinuous evolutions. It is only the exact shape of the P–T path, details that are often difficult to constrain, which is specific for a complex geodynamic evolution. For example, the significance of the amphibolite facies mineralogy is ambiguous. It may either represent a single path that entirely formed in a collision setting; or alternatively, it may merely represent an exhumation stage that formed during ongoing subduction and before final collision (Fig. 5a). In the case of dual peak paths, details regarding amphibolite facies overprint are crucial for better understanding exhumation processes in general and details of the transition from subduction to collision in particular.

The metamorphic data in a geodynamic context

The above-described importance of metasediments and the presented tool of a facies grid with its characteristic mineral assemblages can be well used in the Alps. The Alps are well suited for such a compilation because they are a relatively small and well-investigated orogen (e.g. Frey *et al.* 1974, 1980; Goffé & Chopin 1986; Roure *et al.* 1990; Dal Piaz 2001; Oberhänsli *et al.* 2004; Schmid *et al.* 2004). The Alps are developed by subduction of two different oceans followed by collision between two main continents (Adria and Europe). The relics of the oceans (Piemont–Liguria, Valais) and the separating microcontinent



1: Chl + 4Kln = Qz + 5Car + 2W
2: 2Qz + Kln = Prl + W
3a: 4Prl + Chl = 5Ctd + 14Qz + 3W ($^{Chl}X_{Mg}$=0.4)
3b: 4Prl + Chl = 5Ctd + 14Qz + 3W ($^{Chl}X_{Mg}$=0.7)
4: 5Car + 9Qz = 4Prl + Chl + 2W
5a: Car = Qz + Ctd + W ($^{Car}X_{Mg}$=0.4)
5b: Car = Qz + Ctd + W ($^{Car}X_{Mg}$=0.7)
6: Prl = Ky + 3Qz + W
7: 2Ms + Chl + 2Qz = 3Ctd + 2ACel + W

Fig. 4. Ambiguity of chloritoid-quartz as index assemblage. Depending on the P–T path, chloritoid-quartz can be formed either by breakdown of (Fe, Mg)-carpholite at HP conditions (reaction 5) or by breakdown of pyrophyllite at LP conditions (reaction 3). Chloritoid-quartz assemblage alone cannot be used as index for pressure conditions. Its significance depends on the mineral reaction and on the associated minerals.

(Briançonnais) are still existing and are now sandwiched between Adria and Europe. The palaeogeographic (tectonic) overview of the present-day situation is principally inspired from Schmid *et al.* (2004) and Bigi *et al.* (1990), and can so be combined with metamorphic information of the different units. This approach will be presented below.

Subduction-related minerals and their distribution

All the way from the Adriatic margin preserved in the lower Austroalpine nappes to Europe-derived nappes, the tectonic units (i.e. Piemont–Liguria, Briançonnais, Valais) contain metasediments that recorded the Late Cretaceous–Cenozoic subduction history. The minerals indicating subduction-related processes are listed in Table 2 and their distribution is shown in Figure 6.

We recognize the HP–LT imprint on the European continental margin (Tauern window, Adula nappe and surrounding covers), on all the metasediments derived from the partly oceanic Valaisan domain, as well as on the Piemont–Ligurian realm (Rechnitz window, Matrei zone, Avers, Zermatt–Saas zone, Entrelor, Cottian Alps, Voltri

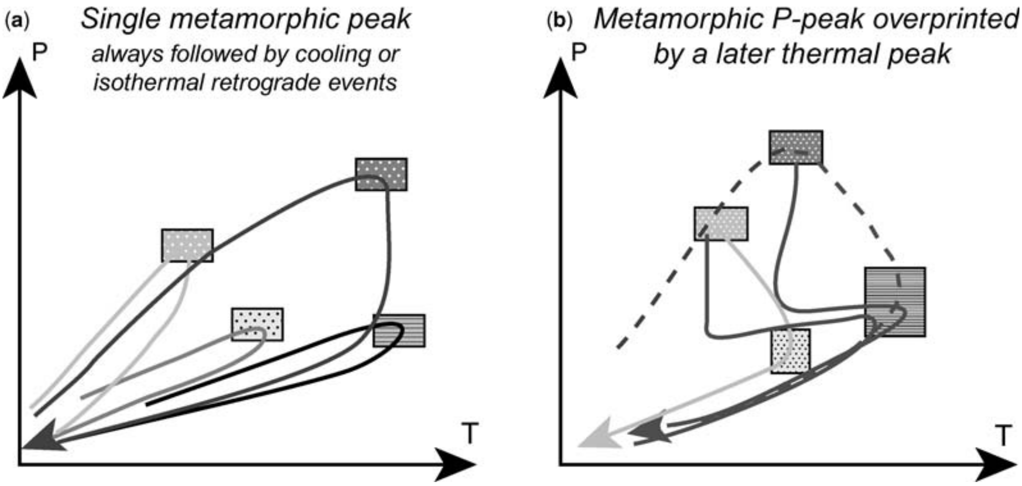


Fig. 5. Ambiguity of some metamorphic facies. (**a**) A rock undergoes a simple metamorphic evolution in a distinct geodynamic setting, leading to only one peak metamorphic paragenesis (simultaneous P and T peaks) followed by later retrogression. (**b**) In some cases, certain metamorphic PT paths show distinct pressure and temperature peaks. The pressure-peak can be related to one geodynamical scenario and it may have been overprinted by a thermal peak that resulted from a second and different geodynamic scenario.

group, Tuscany and Corsica). The situation is more complex for the units derived from the Briançonnais terrane. Going from internal to external, they indicate eclogite and UHP conditions in the 'internal massifs' (Monte Rosa, Gran Paradiso, Dora Maira), blueschist conditions (Suretta cover, Mont Fort, Ruitor, Vanoise, Acceglio, Ligurian Alps, Tenda), and subduction-related greenschist and low-grade conditions (Tasna, Schams, Zone Houillère). Based on structural arguments, some authors dispose of this complexity by changing the palaeogeographic attribution of the 'internal massifs' (Froitzheim 2001; Pleuger *et al*. 2005). We are agreeing with the fact that the geodynamic evolution is complex and that the 'internal massifs' are part of the Briançonnais (see e.g. Polino *et al.* 1990; Borghi *et al.* 1996; Froitzheim *et al.* 1996; Dal Piaz 1999).

In the following, we will present four examples (Cottian Alps, Ruitor, Entrelor and Valais ocean) that document and demonstrate the use of metamorphic studies on metasediments for unravelling different PT evolutions during the early subduction-related history of the Alps.

Continuous P increase within sediments from one single palaeogeographic unit (Cottian Alps). The Schistes Lustrés complex in the Cottian Alps is formed by intensely folded Upper Jurassic (Malm; De Wever & Caby 1981) to Upper Cretaceous calcschists deposited in the oceanic Piemont–Liguria trough (Coniacian–Santonian; Lemoine & Tricart 1986; Deville *et al.* 1992),

Table 2. *Main metamorphic minerals or mineral assemblages found in metasediments in the Alps, classified according to their meaning*

HP–LT 'minerals'	'Low-grade'/ greenschists 'minerals'	HT 'minerals'	'Ambiguous' minerals
Fe, Mg-carpholite Car	margarite (Mgr)	andalusite (And)	chloritoid (Ctd)
lawsonite Lws	pyrophyllite (Prl)	sillimanite (Sil)	kyanite (Ky)
aragonite Arg	kaolinite (Kln)–Quartz	cordierite (Crd)	garnet (Gt)
coesite Cs	riebeckite (Rbk)	staurolite (St)	clinozoisite/zoisite (c/Zo)
talc Tlc	glauconite (Glt)	wollastonite (Wo)	cookeite (Cook)
glaucophane Gln	stilpnomelane (Stl)	diopside (Di) *in marble*	sudoite (Sud)
jadeite Jd	albite–quartz–phengite–chlorite	tremolite (Tr) *in marble*	
	quartz–phengite–chlorite		

with a few mantle slivers (mainly serpentinites) representing the floor of this Alpine realm largely devoid of mafic oceanic crust (Lagabrielle & Lemoine 1997). The study of metamorphic sediments shows that carpholite-bearing assemblages are present in the western part (Goffé & Chopin 1986; Agard *et al.* 2001) while chloritoid-bearing assemblages as well as garnet–lawsonite–glaucophane assemblages in marbles (Ballèvre & Lagabrielle 1994) occur in the eastern part. On the basis of metapelite mineralogy, P–T estimates at maximum pressure increase from west to east across the study area from *c.* 1.2–1.3 GPa at 300–350 °C (Agard *et al.* 2001) to 1.4–1.5 GPa at 450–500 °C (Ballèvre & Lagabrielle 1994; Agard *et al.* 2000).

Bimodal evolution within a single paleogeographic unit (Ruitor area). The metamorphic evolution of the basement units derived from the Briançonnais microcontinent was always a matter of debate (Desmons *et al.* 1999; Monié 1990). In the southwestern Alps, an HP imprint is well documented by occurrences of Fe-Mg-Carpholite (Goffé 1977, 1984; Goffé *et al.* 1973, 2004; Goffé & Chopin 1986), and aragonite (Gillet & Goffé 1988) in metasediments and by occurrences of lawsonite and jadeite in metabasites (Lefèvre & Michard 1965; Schwartz *et al.* 2000). In the northwestern Alps in contrast, only the uppermost unit of the Briançonnais domain (the Mont Fort nappe) displays blueschist facies conditions (Schaer 1959; Bearth 1963).

In the Zone Houillère and in its Permo-Triassic cover as well as in the Briançonnais basement, metamorphic mineral assemblages are mainly composed of white micas with varying chemical composition, chloritoid and garnet. This same assemblage may occur within different lithologies (meta-arkose, meta-pelite, meta-sandstone). The increase in metamorphic grade from greenschist facies conditions in the northwest (Zone Houillère) to the transition between blueschist and eclogite facies conditions in the southeast (Internal Briançonnais) is well documented (Bucher & Bousquet 2007). A major discontinuity in metamorphic grade, as documented by a pressure gap of *c.* 0.7 kbar, is located at a tectonic contact within the Briançonnais terrane, namely that between the Zone Houillère and Ruitor unit (Caby *et al.* 1978; Bucher 2003).

Rock associations displaying different metamorphic peak conditions (Entrelor area). Two types of metamorphic rock (blueschist and eclogites) have been described in this area, which is part of the Piemont–Liguria units of the western Alps (Dal Piaz 1999). Recently, the rock assemblage in the Entrelor area has been interpreted as a metamorphic mix, consisting of eclogitic rocks that were embedded into a blueschist facies matrix consisting of metapelites and greenstones (Bousquet 2008). The two kinds of HP metamorphic rock reveal different peak metamorphic conditions (1.2 GPa at 450 °C vs. 2.3 GPa at 550 °C); it is their contemporaneous exhumation within a subduction channel which juxtaposed them at a shallower crustal level. This evolution illustrates that subduction processes cannot be considered as a single-pass process; instead, return flow of a considerable portion of crustal and upper mantle material must be accounted for (Gerya & Stockhert 2002), and the exhumation of the different rock types cannot be considered independently from each other (Engi *et al.* 2001). The rocks of the Entrelor area can be viewed as an exhumed part of a frozen subduction channel consisting of a mix of metamorphic rocks that have different metamorphic evolutions, and which were accreted at great depths.

Geometry of the subduction (units derived from the Valais ocean). In the eastern and central Alps, blueschist-facies rocks derived from the Valais ocean are exposed structurally below the Austroalpine nappes over an area of $300 \times 20\ \mathrm{km}^2$ (from the Tauern window to the Grisons area) and have a thickness of around 10 km. This large volume of blueschist-facies rocks is in contrast with that of the eclogite-facies rocks of the western Alps that only form a small 2 to 5 km thick slice. The difference in volume and metamorphic conditions from east to west is probably due to a change in style and geometry of subduction.

In the eastern and central Alps, the blueschist metasediments formed within a wide accretionary wedge with a thickness of 40–50 km which underlies the orogenic lid formed by the Austroalpine nappes and they were exhumed before the final collision between the European and Apulian continents (see discussion in Bousquet *et al.* 2002). Subduction occurred at a high angle to the strike of the orogen. In the western Alps, where only a narrow accretionary wedge formed (Ceriani & Schmid 2004), producing low-grade metamorphic conditions (Ceriani *et al.* 2003), subduction occurred in a sinistrally transpressive environment, i.e. at a small angle to strike of the orogen (Schmid & Kissling 2000, Ceriani *et al.* 2001). The blueschist and eclogite facies metasediments of the Versoyen area (Petit St. Bernard and Versoyen units, Goffé & Bousquet 1997) were also subducted and extruded along a N–S direction, i.e. at a small angle to the orogen (Fügenschuh *et al.* 1999). Moreover, the western Alps were never overlain by an orogenic lid formed by the Cretaceous-age Austroalpine nappe stack, but at best by rather thin basement silvers attributed to the Margna–Sesia fragment (Schmid *et al.* 2004).

Despite the fact that metamorphism related to Latest Cretaceous to Cenozoic subduction is scattered all over the Alps, information on these processes is unevenly distributed. Areas with wide occurrences of metasediments (Fig. 1) allow for the best insight into the early geodynamic evolution of the Alps. In the western Alps, all stages of a subduction process in PT frame (from UHP to greenschist conditions), as well its evolution in time (from the latest Cretaceous to the Oligocene, i.e. between 70 and 33 Ma), are recorded. Contrarily in the eastern Alps and in the Tauern window (we exclude the Cretaceous-age high-pressure metamorphism from this discussion since it was related to a different orogeny; Froitzheim *et al.* 1996) the metamorphic record of the metasediments is limited, and the HP rocks only exhibit Eocene ages (45–35 Ma).

Minerals related to collision processes and their distribution

Collision-related minerals apparently do not occur over the whole Alpine edifice. Minerals produced during collision are mainly indicative for temperature-dominated metamorphic conditions (Barrovian-type metamorphism). They occur in the external zones, as well as in the central Alps (Lepontine dome) and in the Tauern window of the eastern Alps (Fig. 7).

In the external zones, the metamorphic evolution reaches maximum lower greenschist conditions, metamorphism resulting from collisional deformation as nappe emplacement, thrusting and folding (Frey & Ferreiro-Mählmann 1999; Burkhard & Goy-Eggenberger 2001; Ferreiro-Mählmann 2001). Burial processes both control metamorphic conditions in the external zones and limit it to low grade. The area of the Lepontine dome and the Tauern window, however, experienced higher metamorphic conditions, at least amphibolite facies.

Three examples will elucidate geodynamic processes that led to high-temperature metamorphic overprinting of metasediments in more internal zones.

Continental underplating (Tauern window). In the post-Variscan metasediments of the Tauern window, a high-temperature event is mainly indicated by the occurrence of Fe–Ca-rich garnet (Droop 1981; Selverstone 1985). Only a few occurrences of staurolite have been reported, indicating maximum amphibolite facies conditions. The mineral distribution pattern indicates two dome-like structures with concentric temperature gradients. This pattern resulted from the underthrusting of Europe-derived continental basement (Kurz *et al.* 1999) and its accretion to the overlying Austroalpine basement complex (Apulian Plate). This geodynamic scenario led to simple and continuous P–T paths (Fig. 6) that indicate decompressional heating from HP conditions into amphibolite facies conditions.

In Schieferhülle, the earlier HP- stage (blueschist facies conditions, Selverstone & Spear 1985) at 36 Ma was overprinted by HT conditions (amphibolite facies conditions) at around 30–27 Ma ago (Christensen *et al.* 1994; Zimmermann *et al.* 1994).

Continental wedging (Lepontine dome). High-temperature metamorphic conditions in the central Alps (the Lepontine area) were based on the study of metasediments in the early works on Alpine geology (e.g. Schmidt & Preiswerk 1908; Preiswerk 1918). Since these pioneering descriptions, several workers have dealt with metasediments from the Lepontine in order to understand progressive metamorphic evolution in isochemical systems (siliceous carbonates system: Trommsdorff 1966; pelitic and marly compositions: Frey 1969). The Lepontine area is characterized by extensive amphibolite facies conditions, reaching migmatization and/or granulite facies conditions. The thermal overprint (Fig. 6) progressively decreases from UHT-conditions in the south to greenschist facies conditions outwards (Streckeisen *et al.* 1974; Engi *et al.* 1995; Todd & Engi 1997). The northern margin of the amphibolite grade Lepontine dome is defined by the appearance of staurolite in pelitic systems. However, to the south it is truncated by the Insubric line, along which granulites and migmatites are juxtaposed to rocks of the southern Alps that did not experience substantial Alpine metamorphism.

Thin Mesozoic metasedimentary bands separate large volumes of basement rocks belonging to various nappes stacked below the Austroalpine nappes and in front of the southern Alps (Apulian Plate). The accretion of vast amounts of crustal material derived from the European margin (Adula, Simano, Leventina) and the Briançonnais terrane (i.e. Maggia nappe) allowed for high radiogenic heat production (Verdoya *et al.* 2001; Roselle & Engi 2002) producing HT assemblages.

The PT paths deduced from the high-grade metasediments often, but not always (see Nagel *et al.* 2002; Keller *et al.* 2005*a* for more simple PT paths), show bimodal trends (Fig. 6): a HP event is followed by a phase of heating (Engi *et al.* 2001; Berger *et al.* 2005; Brouwer *et al.* 2005; Wiederkehr *et al.* 2007). Shortly after the HP event, which probably occurred at around 45 Ma (47–51 Ma Bucher 2003; 42.6 Lapen *et al.* 2007 see discussion in Berger & Bousquet 2008), HT metamorphic conditions prevailed over a long period of time until 30 Ma ago in the south and

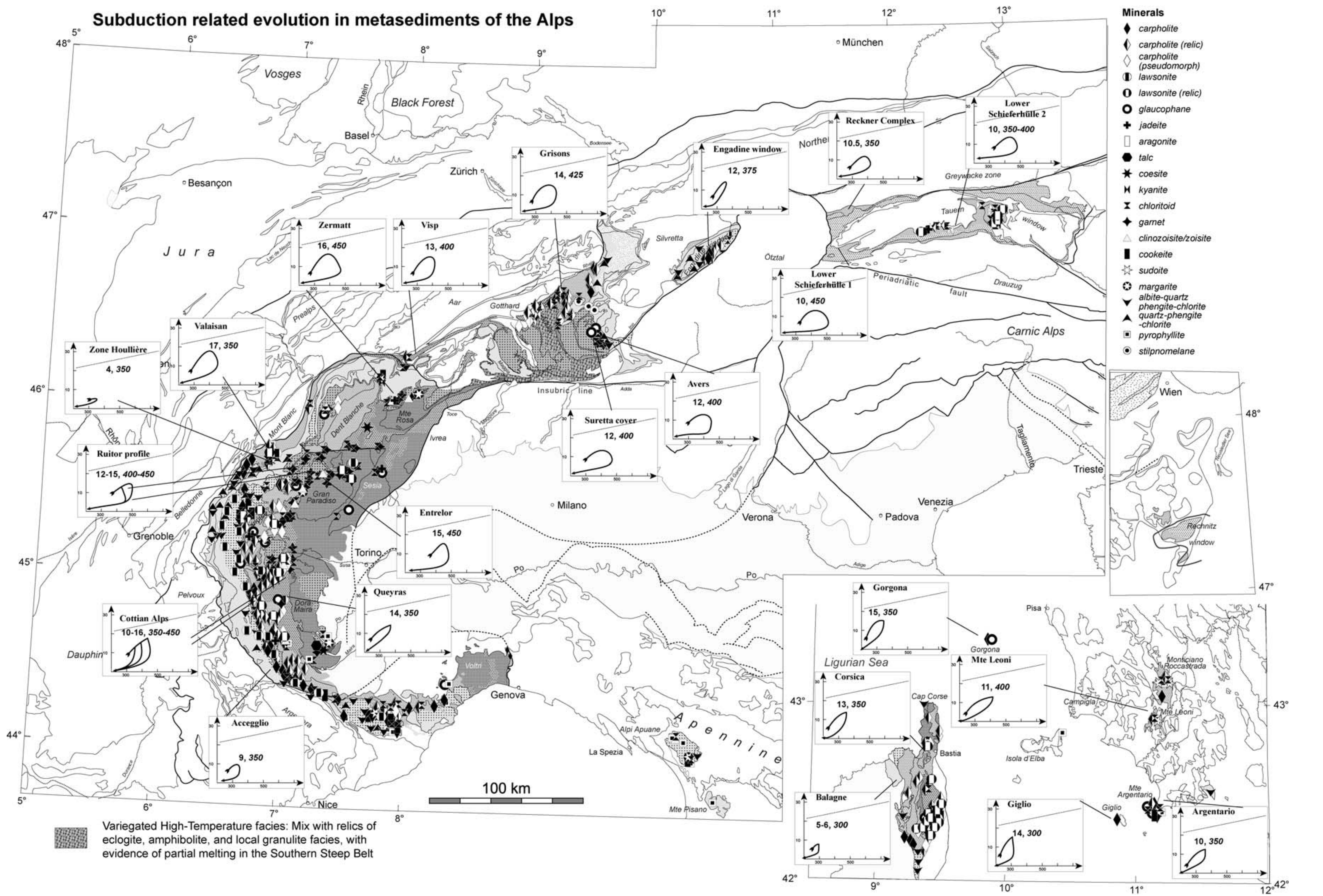


Fig. 6. Mineral distribution (and some associated PT paths) of subduction-related processes in post-Hercynian metasediments of the Alps. We note a wide distribution of HP events over the entire Alpine edifice. See references in Appendix.

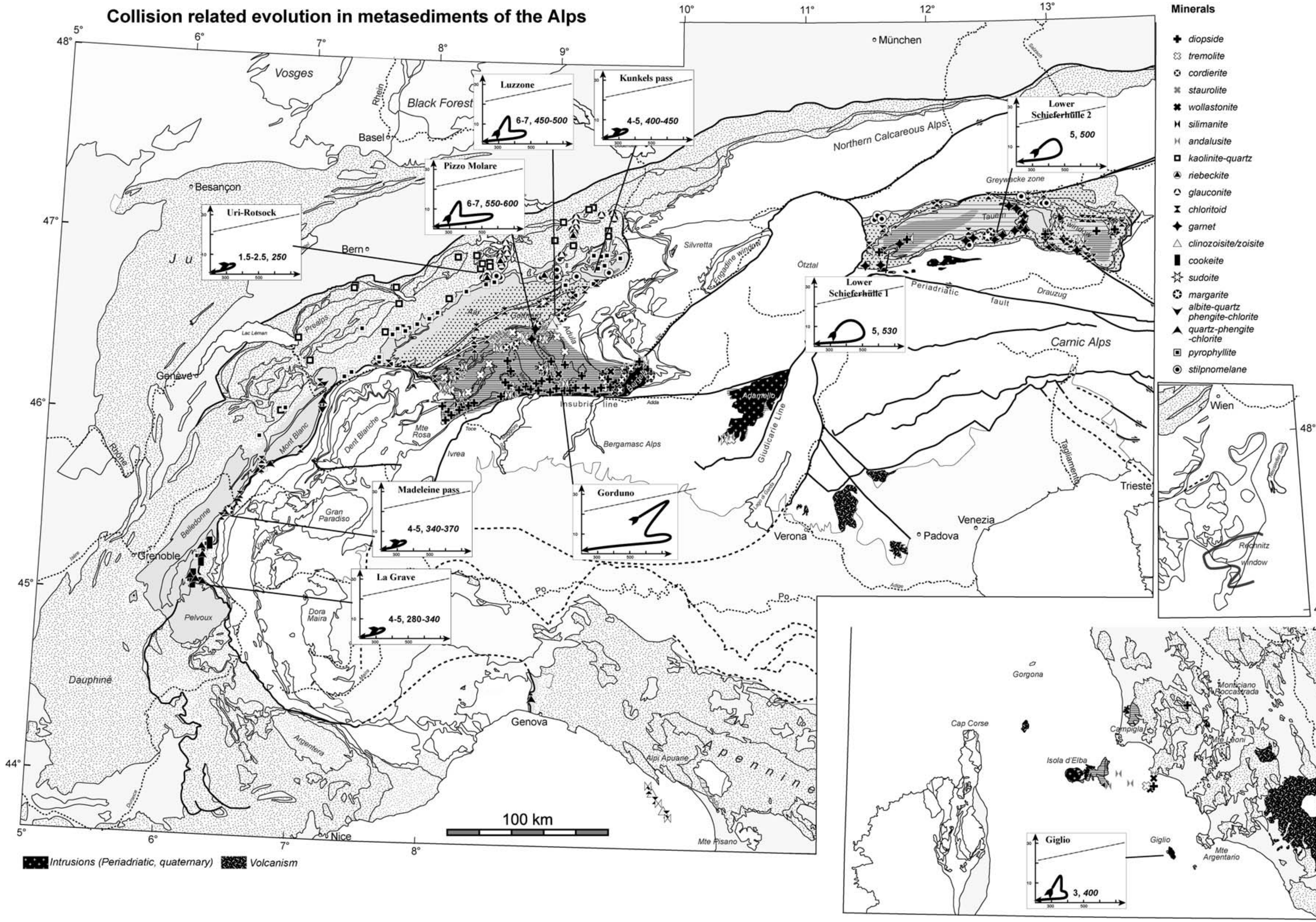


Fig. 7. Mineral distribution (and some associated PT paths) of collision-related processes in post-Hercynian metasediments of the Alps. Two types of metamorphism can be distinguished. The lower one up to greenschist facies conditions has a large distribution all over the Alpine Belt and occurs in the external part. The second type is characterized by an important thermal event from greenschist to granulite conditions. It occurs only in three specific areas (Tauern, Lepontine dome and Tuscany). In these areas, the thermal event can overprint an earlier HP event. See references in Appendix.

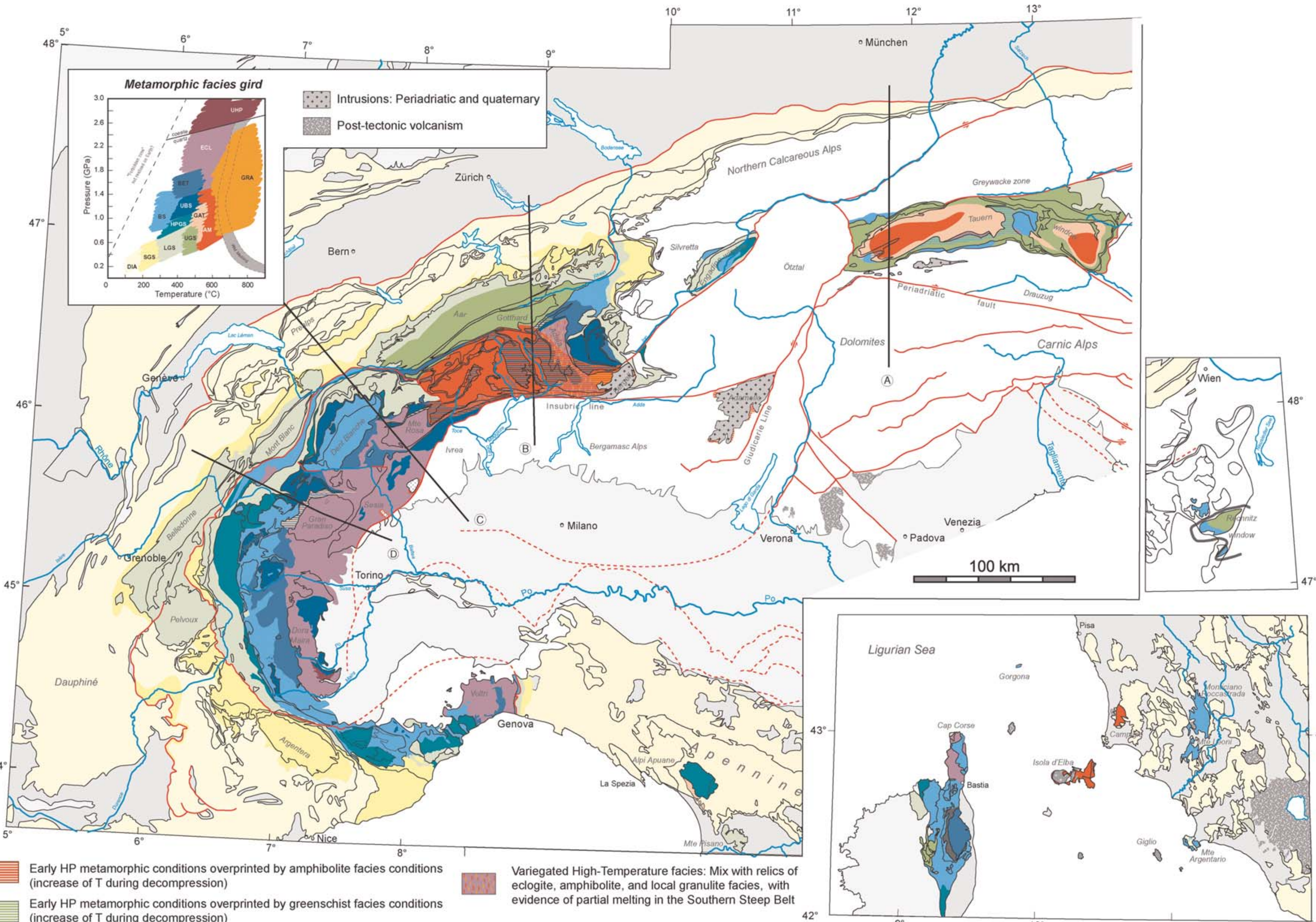


Fig. 8. Metamorphic facies distribution (and related magmatism and volcanism) in the Alps from Vienna (Austria) to Corsica and Tuscany. On the map, the different stages of the geodynamic evolution are indicated. This map, largely modified from Oberhänsli *et al.* (2004) is a synthesis of Figures 6 and 7. Traces of profiles presented on the Figure 9 are indicated.

15 Ma in the north respectively (Hunziker *et al.* 1992).

Post-orogenic heating (Tuscany). In western Tuscany, Quaternary magmatism is witnessed by volcanic as well as intrusive rocks. This magmatism is associated with crustal thinning and high heat flow values (Scrocca *et al.* 2003). Consequently, metasediments not only exhibit HP mineral assemblages, but also minerals such as andalusite, staurolite, chloritoid, epidote that document the high-temperature evolution. A bimodal PT path has been reconstructed from Giglio, indicating both an HP and HT event. (Rossetti *et al.* 1999).

The inferred palaeotemperature distribution pattern resembles an asymmetric thermal high defined by the appearance of kyanite, similar to the present geothermal pattern of the Tuscan crust (Franchescelli *et al.* 1986), as indicated by a series of geothermal anomalies passing through the northern Apennines (Della Vedoya *et al.* 2001). The age of the HT event (from 15 to 8 Ma, Kligfield *et al.* 1986; Brunet *et al.* 2000; Molli *et al.* 2000*a*, *b*) clearly post-dated the HP stage (31–26.7 Ma, Brunet *et al.* 2000) in Tuscany.

Summary. Remnants of the high-temperature event are unevenly distributed throughout the Alps. They are localized in the Tauern window, the Lepontine dome, and in Tuscany. In contrast, large areas lack such an HT overprint: the entire western Alps and the Engadine window located between the Lepontine dome and Tauern window. Both the Lepontine and the Tauern domes are made up of continent-derived granitoid upper crustal metamorphic sequences (Lammerer & Weger 1998; Neubauer *et al.* 1999; Schmid *et al.* 1996), while the Engadine window (Bousquet *et al.* 2002) and the southwestern Alps (Agard *et al.* 2002; Lardeaux *et al.* 2006) are mainly built up of oceanic-metasedimentary sequences.

Hence we conclude that the high-temperature event in the eastern and central Alps is due to large local accumulations of crustal material during continental collision, while in Tuscany it records a post-orogenic event, associated with thinning of the lithosphere (Rossetti *et al.* 1999).

Metamorphic structure of the Alps

Sediments occur throughout mountain belts such as the Alps and represent a large variety of palaeo-environments and chemical compositions. Moreover, several of these compositions are very sensitive to temperature and pressure variations. Thus, they have a high potential for registering the different stages of their geodynamic evolution. Mineral distributions in metasediments, combined with previous works on metabasites, allow the deciphering of the complexity of the Late Cretaceous–Tertiary alpine history (Figs 8 and 9).

Map representation (Fig. 8) allows the clear separation of different areas in the Alps. Corsica and the western Alps as well as the far eastern Alps (Rechnitz window) have recorded only the subduction-related evolution, characterized by HP metamorphism. The central Alps and the eastern Alps (Tauern window) are displaying a more complex history. In these areas, the HP phase is overprinted by higher temperature conditions.

Alpine eclogite facies remnants in the central Lepontine area appear to be restricted to a metamorphic mix (Berger *et al.* 2007). They are isolated occurrences in a belt that includes relics of variegated high-grade metamorphism, from granulite facies to eclogite to amphibolite facies. This structure is interpreted as representing remnants of a tectonic accretion channel (Engi *et al.* 2001), which had developed along the convergent plate boundary during Alpine subduction.

From the metamorphic map (Fig. 8) and using four major geological transects (Schmid *et al.* 2004), we propose metamorphic transects across the Alps down to 15–20 km depth (Fig. 9). In the eastern transect (Fig. 9a, along the TRANSALP profile), the main alpine metamorphic features show the thermal overprint. Only scarce relics of the HP history are preserved. In the central Alps (Fig. 9b, NFP 20 east profile), HP and HT metamorphic rocks coexist. The thermal overprinting of different subduction patterns can be observed: eclogites of the Adula complex, rocks undergone into blueschist conditions (European margin—*north of Adula, Simano*—, Valais, Briançonnais—*Tambo, Suretta*—) as well as rocks that have not been subducted (Maggia nappe for the Briançonnais) have been thermally overprinted by the Late Tertiary event. A wedge-type structure built against the Insubric line can be clearly distinguished on the central Alps profile. In the northwestern Alps (Fig. 9c, NFP 20 west profile), while the subduction-related metamorphism is widespread, the thermal overprinting is limited to the European platform (sediments—*Helvetic nappes or Dauphiné*—, basement rocks—e.g. *Mt Blanc*—) or to the structurally lower units (root of the Mte Rosa, Antrona). In the western Alps (Fig. 9d, ECORS-CROP profile), subduction-related metamorphism is the main record. The thermal overprint appears west of the Penninic front and it is limited to the European platform (Belledonne, Pelvoux, Dauphiné). The most internal units are completely lacking an HT event. It can only be assumed for the deepest units (at around 20 km depth). Two subduction zones, indicated by HP metamorphic conditions, can be

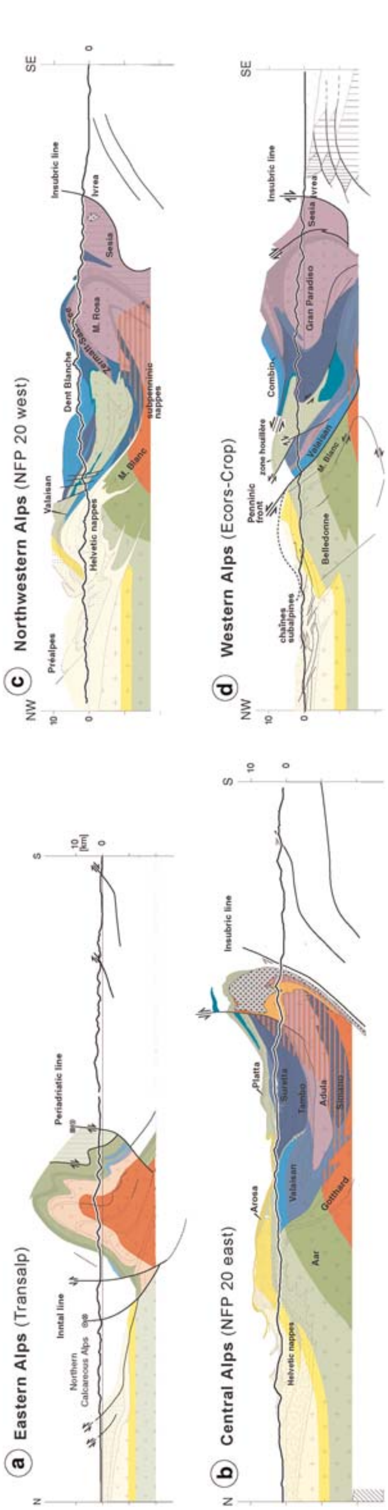


Fig. 9. Metamorphic structure of the Alps. We report metamorphic data along four geological transects of Schmid *et al.* (2004) down to 15–20 km depth. Below this depth, the past metamorphic history should be overprinted by the present thermal regime. (**a**) Eastern transect along the TRANSALP seismic profile. (**b**) Central Alps transect (along the NFP 20 east seismic profile. (**c**) Northwestern Alps transect along the NFP 20 west seismic profile. (**d**) Western Alps transect, along the ECORS_CROP seismic profile.

clearly evidenced. One (in the east) is formed by the Piemont–Liguria rocks, the Gran Paradiso massif and the most internal part of the Briançonnais. The second subduction zone is formed only by the Valais rocks and is rooted at depth. Both zones are separated from each other by the external Briançonnais (Zone Houillère) which lacks evidence for HP metamorphism. The arrangement of the nappe pile in the western Alps clearly shows a subduction-type structure in which most of the tectonic units dip southwestward.

Discussion

Evidence for HP metamorphism recording prolonged subduction processes during at least over 37 Ma (from 70 Ma in Sesia to 33 Ma in Valaisan, see Bousquet *et al.* 2002 and Berger & Bousquet 2008, for timing constraints). The evidence for these long-lasting processes is also widespread over the entire orogen, from the Rechnitz window in the east to Corsica and Tuscany in the southwest. All palaeogeographic units, of continental and oceanic origin, were involved in these subduction processes. The nappes derived from the Penninic–Austroalpine transition zone (Margna–Sesia fragment), the Piemont–Ligurian ocean, the Briançonnais terrane, the Valais ocean and the European margin all were successively subducted under the Apulian Plate (Berger & Bousquet 2008).

In contrast, high-temperature metamorphism is a relative short-lived process, lasting for some 15 Ma (30 to 15 Ma). The evidence for such HT metamorphism is also localized in specific regions. It is limited to areas where considerable amounts of continental crust were accumulated into accreted nappe stacks. High-temperature conditions (more than 650 °C, up to 800 °C; granulites and migmatites) were reached in the Lepontine dome where a huge amount of continental crust allowed for high radiogenic heat production. In the Tauern, a less important amount of imbricated continental crust led to amphibolite facies conditions (up to 600 °C). In the Engadine window (Hitz 1995, 1996), as well as in the western Alps, the relative scarcity of continental crust involved in the orogenic wedge does not allow for such a high heat production and associated high-temperature overprint.

The transition between the western Alps, lacking such an HT overprint, and the Lepontine dome can be observed in the Monte Rosa area. There, only the lower parts exposed in deep valleys (Domodossola) show an amphibolite facies overprint (650 °C, Keller *et al.* 2005*b*).

Thermal overprint is primarily related to the amount of crust involved in the subduction and collision processes (Bousquet *et al.* 1997; Goffé *et al.* 2003) rather than to processes of shear or viscous heating (Burg & Gerya 2005). The latter mechanism, which suppose high deformation rate, will not allow for the preservation of HP–LT assemblages within high-grade rocks, as is found for example in the southern Adula complex (Nagel *et al.* 2002).

The relation between the volume of continental crust imbricated and intensity of high-temperature orogenic metamorphism can be generalized over the entire Alpine edifice, except for Tuscany where the late (<8 Ma) thermal overprint is clearly related to lithospheric thinning.

Conclusions

Based on metamorphic studies in metasediments, we evidence substantial differences in the metamorphic and hence the geodynamical evolution along strike of the Alpine orogen.

The western Alps did not reach the mature stage of a head-on colliding belt as is indicated by a continuous metamorphic evolution, representing all the subduction-related processes ranging from lower greenschist to UHP conditions. All the metamorphic rocks behind the Pennine frontal thrust were already exhumed to upper crustal level during ongoing oceanic and continental subduction and before collision with the Dauphinois domain from around 32 Ma onwards (Fügenschuh & Schmid 2003; Leloup *et al.* 2005). Hence, the western Alps represent a frozen-in subduction zone. Since then, only exhumation by erosional processes affected the inner parts of the orogen.

The rest of the Alpine orogen later underwent a more important collision process due to the ongoing head-on geometry of subduction and collision. It therefore often but not always shows a bimodal metamorphic evolution with two distinct P and T peaks. The intensity of the thermal overprint relates to the amount of crustal material incorporated to the orogenic wedge.

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Appendix

List of the references used to build the maps on Figures 5–7.

Eastern Alps: Bousquet (this study), Bousquet *et al.* (1998), Dachs (1986, 1990), Droop (1981, 1985), Franz (1983), Höck (1974, 1980), Leimser & Purtscheller (1980), Matile & Widmer (1993), Miller *et al.* (2007), Selverstone *et al.* 1984.

Central Alps: Bousquet (this study), Bousquet *et al.* (2002), Droop & Bucher-Nurminen (1984), Frey (1969, 1978), Frey & Niggli (1972), Frey & Wiedeland (1975), Frey *et al.* (1973, 1974, 1980), Frey & Ferreiro-Mählmann (1999), Goffé & Oberhänsli (1992), Irouschek (1983), Oberhänsli *et al.* (1995, 2003), Niggli & Niggli (1965), Staub (1926), Trommsdorff (1966), Wiederkehr *et al.* (2007).

Western Alps: Agard *et al.* (2000, 2001), Ballèvre (1988), Ballèvre & Lagabrielle (1994), Bousquet (2007), Bousquet *et al.* (2004), Bucher & Bousquet (2007), Caron & Saliot (1969), Caron (1974), Ceriani *et al.* (2003), Chopin (1981, 1984), Chopin *et al.* (2003), Cigolini (1995), Desmons *et al.* (1999), Gillet & Goffé (1988), Goffé (unpub.), Goffé *et al.* (1973), Goffé (1977, 1982, 1984), Goffé & Chopin (1986), Goffé & Velde (1984), Goffé & Bousquet (1997), Goffé *et al.* (2004), Henry (1990), Jullien & Goffé (1993), Le Bayon *et al.* (2006), Leikine *et al.* (1983), Martinotti (unpub.), Saliot (1979), Venturini (1995).

Corsica and Tuscany: Caron & Péquignot (1986), Caron (1994), Daniel & Jolivet (1995), Daniel *et al.* (1996), Franceschelli *et al.* (1986, 1989), Franseschelli & Memmi (1999), Giorgetti *et al.* (1997), Goffé (unpub.), Goffé (1982), Jolivet *et al.* (1998), Leoni *et al.* (1996), Molli *et al.* (2006), Rossetti *et al.* (1999, 2001), Theye *et al.* (1997), Tribuzio & Giacomini (2002).

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