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EXPLANATORY NOTES TO THE MAP: METAMORPHIC STRUCTURE OF THE ALPS AGE MAP OF THE METAMORPHIC STRUCTURE OF THE ALPS – TECTONIC INTERPRETATION AND OUTSTANDING PROBLEMS

by

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Abstract

The mapped distribution of post-Jurassic mineral isotopic ages in the Alps reveals two metamorphic cycles, each consisting of a pressure-dominated stage and a subsequent temperature-dominated stage: (1) a Late Cretaceous cycle in the Eastern Alps, indicated on the map by purple dots and green colours; and (2) a Late Cretaceous to Early- to Mid-Tertiary cycle in the Western and Central Alps, Corsica and the Tauern window, marked on the map with blue and red dots and yellow and orange colours.

The first cycle is attributed to the subduction of part of the Austroalpine passive margin following Jurassic closure of the Middle Triassic, Meliata-Hallstatt ocean basin. This involved nappe stacking, extensional exhumation and cooling.

The second cycle is related to the subduction of the Jurassic-Cretaceous, Liguro-Piemont and Valais ocean basins as well as distal parts of the European and Apulian continental margins. Subsequent exhumation and cooling of the Tertiary nappe pile occurred during oblique indentation of Europe by the Apulian margin in Oligo-Miocene time. Despite a wealth of geochronologic work in the Alps, there are still large areas where relevant data are lacking or where existing data yield conflicting interpretations. Most such conflicts reflect the difficulty of relating the behaviour of mineral isotopic systems to the formation of structures and to the stability of metamorphic mineral assemblages. The age map of metamorphic structure thus also points to areas of future research in the Alps.

Introduction

This map is a compilation of metamorphic ages in the Alps grouped according to tectonic episodes that have been recognized on the scale of the Alpine orogen. As such, it represents a departure from the more traditional approach of distinguishing pre-Alpine and Alpine ages or from depicting the age data in the most objective possible fashion, usually as a forest of sample location points and numbers. In fact, this map is rather more interpretative, because it is based on the correlation of metamorphic mineral assemblages with structures (faults, foliations, folds) that can be related to kinematically distinct tectonic events. It therefore sacrifices objectivity from the metamorphic and geochemical standpoints in favour of a synthetic approach that allows one to regard Alpine metamorphism in a broad geodynamic context. It is intended as an aid to the tectonic interpretation of the Map of the Metamorphic Structure of the Alps.

When referring to metamorphism as "Alpine”, we mean metamorphism in the Alps that post-dates the deposition of marine sediments in Mesozoic ocean basins and adjacent continental margins of the Alps. These sediments range in age from Early Triassic to Early Tertiary, with syn-rift sedimentation being older in the Eastern Alps (Middle Triassic) than in the Central and Western Alps (Early to Middle Jurassic). The term "Alpine” is therefore used in both temporal and spatial senses. This dualistic convention is sometimes confusing to extra-Alpine colleagues!

The ages of metamorphism in the Alps were recently reviewed in a series of excellent papers accompanying the 1999 version of the Metamorphic Map of the Alps. The reader is especially referred to DESMONS et al. (1999a-c) and FREY et al. (1999) for the Western and Central Alps, to HOINKES et al. (1999) and THÖNI (1999) for the Eastern Alps, and to COLOMBO & TUNESI (1999) for the Southern Alps. This paper is therefore intended as a supplement to, not a replacement of, this previous work. The breadth of these reviews allows us to restrict citations below to papers published since 1999 or to earlier articles in the Alpine literature that are essential to understanding this map. This paper should therefore be regarded as a guide to reading the map rather than as a full-fledged review. Accordingly, the reference list includes metamorphic literature used to construct the map and, where appropriate, some selected tectonic literature.

Following brief descriptions of the tectonic base map and the colour schemes used to distinguish metamorphic age patterns in the Alps, we discuss some of the problems in dating Alpine metamorphism and in assigning ages to mapped units. The next chapter is devoted to the tectonic interpretations proposed in recent years to account for the distribution of Alpine metamorphic ages. We conclude with some remarks on combining tectonic and metamorphic information in the Alps as a requisite for use of the Alps as a natural laboratory for studying crustal processes.

The tectonic base map

The base map for the metamorphic ages is a simplified and modified version of the recently compiled Tectonic Map of the Alps (SCHMID et al., 2004), itself based on sheets 1 and 2 of the Structural Model of Italy (BIGI et al,. 1991). The black lines represent major tectonic boundaries and basement-sediment contacts. The tectonic boundaries include the contacts of main nappe units in both sedimentary and basement rocks. Other tectonic contacts in the map of SCHMID et al. (2004), all of them secondary in importance, were omitted because they are not related to the distribution of metamorphic ages on the map scale at hand.

Ophiolites marking sutures between the former continental margins in the Alps are not distinguished on the map. These sutures are shown in Figs. 1 and 2, and only partly coincide with the Late Cretaceous and Early Tertiary, pressure-dominated metamorphic events represented by variously coloured dots in the metamorphic structure map.

The reddish-purple lines represent the main segments of the Periadriatic Fault System (PFS). This fault system was active from about 35 Ma to 10-15 Ma and significantly modified the Tertiary Alpine edifice (SCHMID & KISSLING, 2000; HANDY et al., 2004). The Oligocene to Miocene activity of these faults is closely related to the areal distribution of Tertiary overprinting metamorphism in the Alps. This is especially true of mylonitic rocks along the Tonale and Canavese segments of the PFS and of low-angle normal faults flanking the Tauern and Lepontine metamorphic domes, as depicted in Fig. 1 and discussed below.

Topographic features in the map include the major lakes and rivers, as well as the largest cities. The drainage pattern of these lakes and rivers reflects Plio-Pleistocene glaciation and fluviatile activity, which was itself channelled by many of the middle- to late Tertiary tectonic lineaments shown in reddish purple (e.g., FRISCH et al., 1998). This is potentially interesting to map users because some workers have argued that erosional denudation controlled exhumation and cooling of the metamorphic basement in the core of the Alps (SCHLUNEGGER & HINDERER, 2001; SCHLUNEGGER & WILLET, 2002).

The metamorphic age patterns

The colour patterns on the tectonic base map represent two broad categories of metamorphic ages related to the tectonic evolution of the Alps:

1) *Dotted areas* depict tectonic units that were subducted to depths corresponding to high-pressure greenschist-, blueschist-, and eclogite-facies conditions. These are the HPGS, BS, UBS, BET, ECL fields on the map of Metamorphic Structure of the Alps. The purple, blue and red colours of the dots indicate the three broad age ranges of subduction-related deformation and metamorphism, as discussed below. Solid dots represent relatively well constrained ages, whereas open dots indicate areas in which the available ages are sparce, controversial, or even contradictory, and have therefore been constrained by indirect lines of argument.

The age of high-pressure metamorphism is estimated with high-retentivity isotopic systems, including Sm-Nd and Hf-Lu on high-pressure assemblages. In part of the Western Alps, we also cited U-PB SHRIMP ages on zircons from leucosomes in eclogite. We purposely avoided using ages of high-pressure minerals and mineral assemblages that were obtained in the absence of detailed element analyses before about 1990. Many of these first-generation ages are controversial or even meaningless because they were derived from low-retentivity isotopic systems and were affected by partial resetting during temperature-dominated metamorphism or hydrothermal activity (e.g., K-Ar white mica, discussion in HAMMERSCHMIDT & FRANK, 1991).

2) *Solidly coloured* areas indicate rock units that underwent temperature-dominated metamorphism from sub-anchizonal to upper amphibolite facies conditions, including partial melting. This includes the DIA, SGS, LGS, UGS, GAT, AM and VT fields of the metamorphic structure map. Where pressure- and temperature-dominated metamorphism coincide in space in the Alps, the latter always overprints the former.

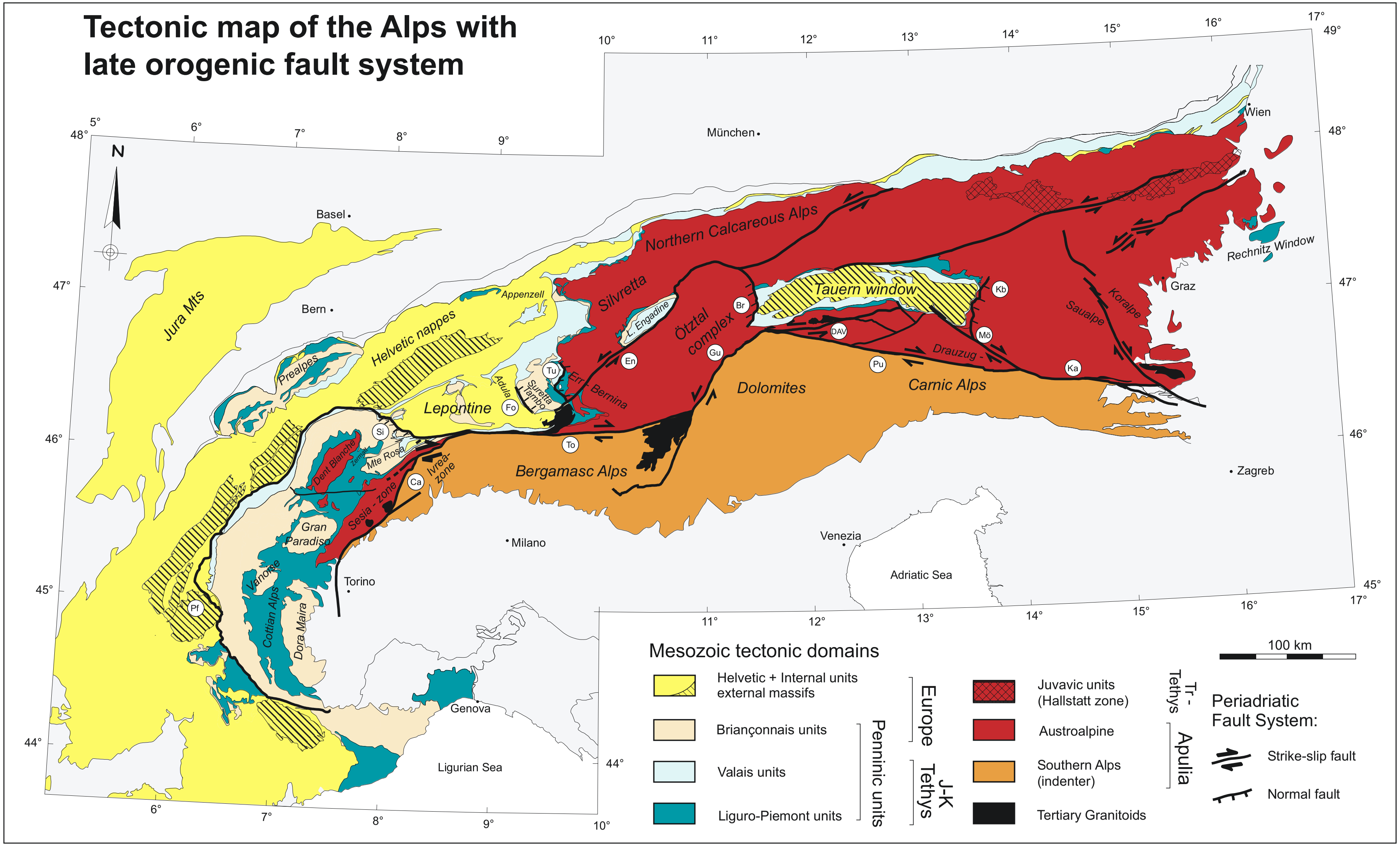
Tectonic map of the Alps with late orogenic fault system

Figure 1

Tectonic map of the Alps after Handy et al. (2004) with names of tectonic units and segments of the late orogenic, Periadriatic fault system (thick lines) discussed in the text: Kb = Katschberg extensional fault, Ka = Karawanken fault, Mö = Mölltal fault, Pu = Pustertal fault, DAV = Defereggen-Antholz-Vals fault, Br = Brenner extensional fault, Gu = Giudicarie fault, En = Engadine fault, Tu = Turba extensional fault, To = Tonale segment of the Insubric mylonite belt, Fo = Forcola extensional fault, Ca = Canavese segment of the Insubric mylonite belt, Si = Simplon extensional fault, Pf = Penninic frontal thrust.

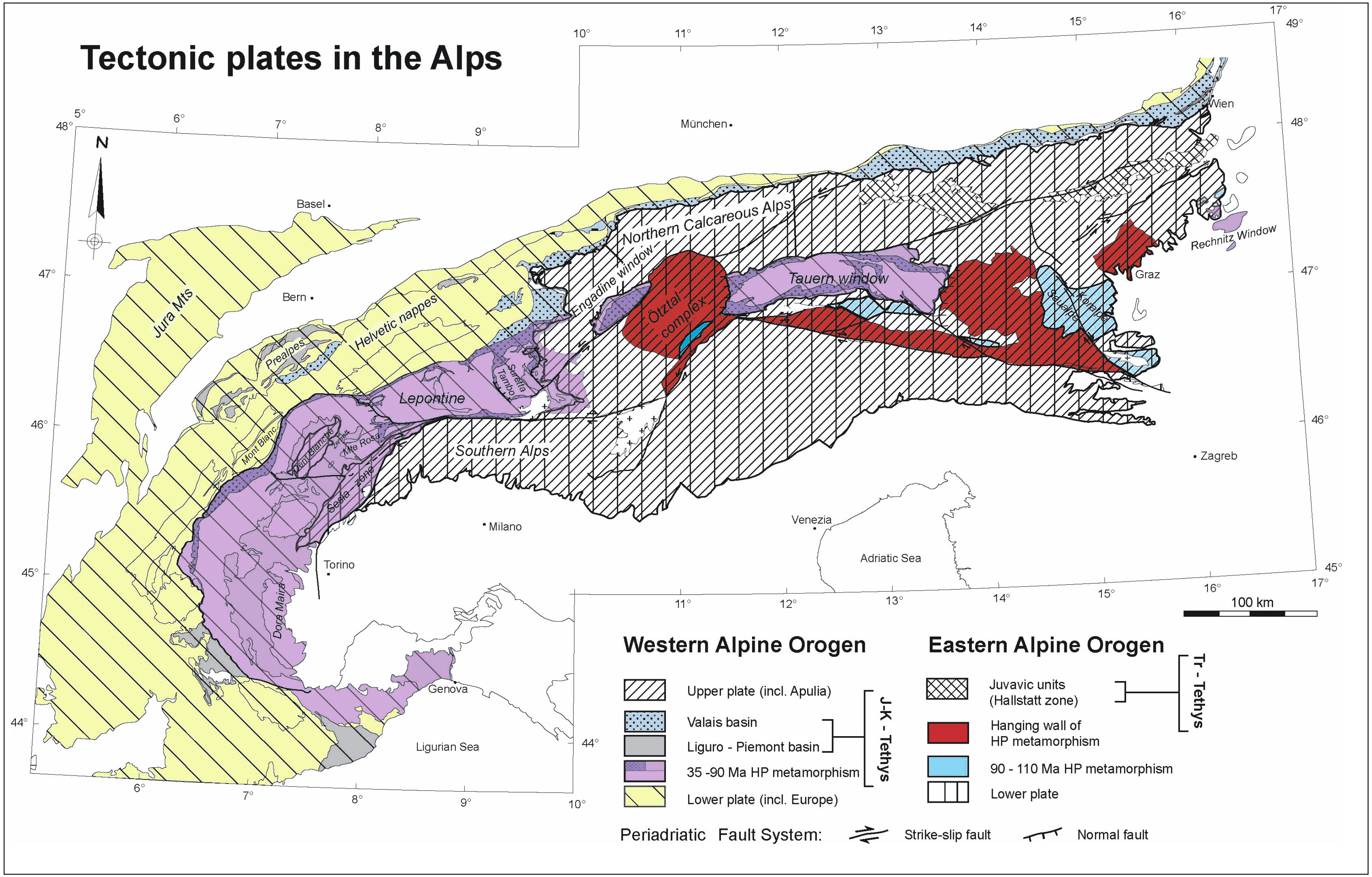

Figure 2

Tectonic map of the Alps after Handy et al. (2004) showing boundaries of the upper and lower tectonic plates, oceanic sutures, and units of both plates affected by HP metamorphism. Base of upper plate in the Eastern Alps from Schuster (2003). See text for explanation.

The temperature-dominated metamorphism is divided into two age groups, 0-59 Ma and 60-110 Ma, depicted with yellow-orange and green shades of colour. These groups are related to the kinematically distinct, Late Cretaceous and Tertiary orogenic events in the Alps (SCHMID et al., 1996; STAMPLI et al., 1998). Each group is further divided into two colour subgroups (yellow and orange for the 0-59 Ma range, light green and dark green for the 60-110 Ma range) in order to distinguish areas that experienced maximum temperatures below 300°C from those where temperatures exceeded this value. This colour distinction based on temperature was both necessary and convenient; necessary because for the radiometric age systems used in dating (Rb-Sr, Ar-Ar and K-Ar biotite and white mica) 300°C represents the effective lower limit for intragranular diffusion of radiogenic Ar and Rb, even in fine grained mica aggregates; convenient because 300°C marks the transition from fracture and frictional sliding to dislocation glide and creep in quartz deformed at geological strain rates (reviews in SNOKE & TULLIS, 1998; STÖCKHERT et al., 1999). Structural studies have shown that quartz aggregates usually govern the bulk strength of granitic rocks in the intermediate continental crust (e.g., HANDY et al., 1999). Thus, in rocks where 300°C was never attained, Rb-Sr, Ar-Ar and K-Ar biotite systems generally yield formational ages, indicating rocks where deformation at that time was brittle. In rocks above this temperature, the same mica systems yield cooling ages and show where deformation prior to and during that time involved viscous, mylonitic creep. Where age data from two systems whose closure temperatures straddle 300°C (e.g., mica ages and zircon fission track ages) are lacking, the trace of the 300°C isotherm on the tectonometamorphic age map was drawn parallel to the boundary between sub-greenschist and greenschist facies on the metamorphic map.

For areas with a sufficiently dense distribution of published radiometric ages, concordant Rb-Sr and K-Ar biotite cooling ages were contoured to show the cooling pattern of the thermal overprint (data compiled by HUNZIKER et al., 1992; MOST, 2003; SCHUSTER, personal communication and SCHUSTER et al., 2004, this volume). In areas where there are very few published data or where the ages vary, an approximate age or range of ages is printed on the map. Ticks on dashed contours delimit areas with mixed mica ages from those with primarily Alpine cooling ages. Mixed mica ages occur frequently in pre-Mesozoic basement rocks where weak Alpine metamorphism overprinted an older Paleozoic metamorphism (see inset to Metamorphic Map of the Alps, 1999 and review thereof in FREY et al. 1999).

The ages of low-grade and sub-greenschist facies metamorphism are difficult to constrain given the low temperatures and lack of dateable minerals under such conditions. In most cases, the metamorphic age is best constrained by the age of the youngest sediments affected by metamorphism (see HOINKES et al., 1999; DESMONS et al., 1999b, c). In this way, the broad ranges of Tertiary and Cretaceous ages were extrapolated over large volumes of sediment in the Alpine fore- and hinterlands. Unfortunately, the very limited number of published mica formational ages in such rocks precluded any age contouring of low-grade metamorphism.

Horizontal orange and thin green stripes in narrow parts of Austroalpine units just east and southwest of the Tauern window indicate overprinting of 60-110 Ma metamorphic ages during 0-59 Ma temperature-dominated metamorphism and deformation. These are the only areas in the Alps where metamorphism related to the Late Cretaceous cycle was overprinted by the Latest Cretaceous to predominantly Tertiary cycle.

Problems in dating Alpine metamorphism

Assigning unequivocal metamorphic ages to some parts of the Alps is difficult due to several circumstances: (1) Discrepancies in the metamorphic ages derived from different systems that have been applied to the same rocks, minerals or mineral assemblages; (2) Contradictions between radiometric and sedimentary ages; (3) A dearth or even lack of reliable ages.
Most of these problems concern the age of pressure-dominated metamorphism. This is not surprising given the relatively sluggish reaction kinetics at the temperatures of high-pressure conditions, the potentially high rates of exhumation of high-pressure rocks and the overprint of the pressure-dependent assemblages by temperature-dominated metamorphism. In addition, most of the ages on high-pressure (HP) assemblages must be interpreted as minimum ages, because geochronometers are strongly temperature-dependent and the thermal peak of metamorphism often followed the baric peak. Below, we consider these problems in some key areas, but hasten to add that our coverage of such problems is far from complete. As stated above, our citation of previous work is selective rather than all-inclusive.

Austroalpine units in the Western Alps

Varied ages are obtained for pressure-dominated metamorphism of Austroalpine units in the Western Alps: The structurally highest of these units, the Sesia Zone (Fig. 1), contains Late Cretaceous eclogites and blueschists (blue dots on the map). The age range is well established by 69 ± 2.7 Ma Hf-Lu ages on coexisting garnet and phengite (DUCHENE et al., 1997), ca. 65 Ma U-Pb SHRIMP ages on zircons from leucosome in eclogite (RUBATTO et al., 1999), and a plethora of Rb-Sr phengite ages ranging from 60 to 90 Ma (DAL PIAZ et al., 2001; OBERHÄNSLI et al., 1985 and references in HUNZIKER et al., 1992; DESMONS et al., 1999c). The phengite ages also constrain the age of HP metamorphism due to the proximity of the 500°C closing temperature in the Rb-Sr phengite system to the maximum temperatures of 500-650°C reached at, or soon after, the baric peak of metamorphism (KOONS, 1986, TROPPER & ESSENE, 2002).
The Pillonet klippe is similarly situated at the top of the Western Alpine nappe pile and yields a 75 Ma $^{40}Ar/^{39}Ar$ phengite age from an eclogite (CORTIANA et al., 1998). Blueschist-facies assemblages in the Dent Blanche klippe (Fig. 1, AYRTON et al., 1982) have not been dated yet, but on the age map we assigned them a similar 60-90 Ma age range to the Sesia Zone (open blue dots) based on the structural continuity of this klippe with the Pillonet klippe and the Sesia Zone.
The remaining Austroalpine units (Mont Emilius, Glacier-Raffay, Etirol-Levaz) are imbricated with the underlying, Early Tertiary nappe pile. Some of these units are so small as to be barely visible on the age map. All of them yield Early Tertiary, Rb-Sr phengite ages (DAL PIAZ et al., 2001): 40-49 Ma in the Mont Emilius klippe, and 45-47 Ma in the Glacier-Raffay and Etirol-Levaz outliers. A 92 Ma $^{40}Ar/^{39}Ar$ phengite age from the Glacier-Raffay outlier is interpreted to reflect Ar overpressure and therefore has no geological relevance. Taken together, these 40-50 Ma phengite ages are identical within error to ages from high-retentivity mineral isotopic systems in HP- and UHP-assemblages of the underlying Zermatt-Saas and Monte Rosa units (DAL PIAZ et al., 2001; LAPEN et al., 2004; and references in DESMONS et al., 1999c). As mentioned above, these varied HP metamorphic ages are attributed to Early Tertiary imbrication of a series of Jurassic extensional allochthons at the transition of the Liguro-Piemontese ocean and the Austroalpine continental margin (DAL PIAZ et al., 2001).

We note that previously produced Late Cretaceous Rb-Sr whole rock and mineral isochron (ga-cpx-plag) ages for eclogite-facies metagranites in the Sesia Zone (OBERHÄNSLI et al., 1985) are not geologically relevant, as they rest on very shaky analytical and methodological foundations (K. HAMMERSCHMIDT, pers. comm.): (1) No analytical error is listed for any of the samples; (2) Of the 12 sample points used to calculate the whole-rock isochron, only eight analyses are listed in the data table and none of them has the ^{87}Rb/^{86}Sr value of 3.5 at the righthand end of the isochron; (3) Of the samples plotted on the sample location map in their Fig. 1, two are not used for the isochron and only one is listed in the data table. Even if one disregards these problems, recalculation of the isochrons with the original data and the newest regression techniques (LUDWIG, 2000) yields a Rb-Sr whole rock age of 153 ± 75 Ma (Sr initial of 0.7130 ± 0.018) and a Rb-Sr ga-cpx-plag isochron of 114 ± 23 Ma (Sr initial of 0.7150 ± 0.00052). The errors calculated above are only minimal as they do not include the unknown analytical error. Even more importantly, both ages are entirely inconsistent with the HP metamorphic ages obtained in more recent studies, as well as with the regional geological context discussed below.

Schistes Lustrés and European basement units in the Western Alps

Conflicting ages of HP metamorphism are obtained with high-retentivity systems from ophiolitic units and Bündnerschiefer (Schistes Lustrés) in the Monviso area (Lago Superiore) near the Dora Maira basement unit (Fig. 1), as discussed by DESMONS et al. (1999c) and BRUNET et al. (2000): A Sm-Nd garnet-clinopyroxene isochron yields 60-62 Ma (CLIFF et al., 1998), whereas a Hf-Lu whole rock-garnet isochron yields 49 Ma (DUCHENE et al., 1997). These ages are certainly younger than the Cretaceous ages previously obtained with lower retentivity mica systems and systems prone to Ar overpressure (SCAILLET, 1996). The 10-15 Ma discrepancy in the high-retentivity ages is puzzling, especially because in other parts of the Alps, HP ages in the 60-90 Ma range are restricted to formerly subducted, Lower Austroalpine units.

A study of Sm-Nd systematics in the same samples analyzed by DUCHENE et al. (1997) revealed that the garnets contained submicroscopic inclusions with low Sm/Nd ratios (LUAIS et al., 2001). These ratios are indicative of crustal contamination processes, e.g., pulses of fluid, and lead LUAIS et al. (2001) to conclude that the 60-62 Ma isochron age cited above is apparent. Since then, AGARD et al. (2002) obtained ^{40}Ar/^{39}Ar phengite ages in the 55-60 Ma range for HP metamorphism along an east-west transect of the Schistes Lustrés in the Cottian Alps (Fig. 1). Phengites that grew during later deformation yield 45-51 and 35-40 Ma ^{40}Ar/^{39}Ar age clusters, with the latter cluster interpreted as the age range of retrograde, greenschist-facies metamorphism associated with extensional exhumation and cooling (AGARD et al., 2002). Similarly, MEFFAN-MAIN et al. (2004) recently obtained a 43 Ma Rb-Sr apatite-phengite isochron on HP assemblages of the Gran Paradiso basement (Fig. 1). Greenschist-facies overprinting in the same unit occurred in the interval of 34-36 Ma.

Further to these studies, two geologic arguments support an Early Tertiary age of HP metamorphism in all Liguro-Piemont and European (Brianconnais) units of the Western Alps: (1) the Liguro-Piemont units in the Western Alps are lithologically and tectonically continuous, so that the well-documented Eocene ages of HP- and UHP metamorphism in the vicinity of the Zermatt-Saas and Monte Rosa units (cited below) also pertain elsewhere in the same units; (2) the metamorphic ages cannot be older than the stratigraphic age of the youngest protolith sediments (Paleocene-Lower Eocene in the Briançonnais cover and Ligurian Alps, DEBELMAS

& DESMONS, 1997; DESMONS et al., 1999b; Upper Cretaceous in the Combin Zone, DEVILLE et al., 1992 and references therein, DESMONS et al., 1999b). In light of the results and arguments above, we extrapolated the 35-60 Ma age interval for pressure-dominated metamorphism all over the Western Alps to include areas where no data are currently available (open red dot pattern).

Corsica

The age of HP metamorphism on western (Alpine) Corsica is also controversial. A Sm-Nd whole rock-Grt-Gla-Cpx isochron age of 83.8 ± 4.9 Ma in an eclogitic lense intercalated with Schistes Lustrés (LAHONDRE & GUERROT, 1997) provides the only evidence of a Cretaceous HP event in the Schistes Lustrés. This is apparently consistent with the observation that Eocene sediments which lack HP assemblages rest unconformably on basement of western Corsica as well as on the Schistes Lustrés (DESMONS et al., 1999c). On the other hand, HP assemblages in the Inzecca units that are thrust onto sediments with reworked, late Lutetian nummulites seem to indicate that pressure-dominated metamorphism was younger than 41 Ma (references in DESMONS et al., 1999c). BRUNET et al. (2000) conducted ^{40}Ar/^{39}Ar studies using conventional and spot laser ablation and found two or more generations of white mica in rock samples. These white micas have a large, discordant spread of ages (35-65 Ma) with evidence of isotopic heterogeneities related to the presence of K-poor phyllosilicate. Therefore, the authors consider that only the minimum 35 Ma age is possible, consistent with 34-40 Ma ^{40}Ar/^{39}Ar phengite ages of MALUSKI (1977) and LAHONDERE (1991). ^{40}Ar/^{39}Ar ages in the 25-35 Ma range are interpreted to date greenschist-facies overprinting during extensional shearing (BRUNET et al., 2000).

The Tenda Massif is a large gneiss dome located to the west of the Schistes Lustrés, and represents part of the distal European margin. The presence of Bartonian nummulites in a metamorphic conglomerate containing blue amphiboles indicates that HP greenschist-facies metamorphism in the Tenda massif and Corté imbricates is less than 37 Ma (BÉZERT & CABY, 1988). This contradicts two early dating attempts: A crude, two-step discordant 40Ar/39Ar age spectra on glaucophane of about 90 Ma, interpreted as the age of the thermal peak (MALUSKI, 1977), and a Rb-Sr whole-rock age of 105 ± 8 Ma for the East Tenda extensional shear zone (COHEN et al., 1981). More recent ^{40}Ar/^{39}Ar ages of BRUNET et al. (2000) on coarse, high-Si phengites yield 34-45 Ma plateaus, which are interpreted as the age of the pressure-dominated metamorphism. Smaller phengites yield ca. 25 Ma, interpreted as the age of top-E extensional shearing in the East Tenda extensional shear zone (BRUNET et al., 2000). Fission track ages also point to Oligo-Miocene exhumation of this shear zone (JAKNI et al., 1998), which is believed to have exhumed HP rocks in its footwall (e.g., JOLIVET et al., 1991).

The recent isotopic evidence for an Early Tertiary age of HP metamorphism on Alpine Corsica is backed up by regional geological arguments as above in the Western Alps: The close lithological and tectonic affinity of the Schistes Lustrés and Tenda massiv on Corsica, respectively, with the Schistes Lustrés and European basement units in the Western Alps strongly supports the idea that HP metamorphism on Alpine Corsica is also Early Tertiary age. This is consistent with paleogeographic reconstructions of STAMPFLI et al. (1998). The age map of Corsica is therefore filled with open red dots to reflect this expectation.

Central Alps

Age determinations on HP assemblages and stratigraphic age constraints in the Central Alps indicate Early Tertiary closure and subduction of the Liguro-Piemont basin including the formation of a Paleocene accretionary wedge at the boundary with the upper plate, Apulian continental margin (review and references of age data in FREY et al., 1999). This was followed by Late Eocene subduction of European (Briançonnais) basement between the previously sutured Liguro-Piemont basin to the southeast and the Valais basin to the northwest (SCHMID et al., 1996, 1997; STAMPFLI et al., 1998).

For example, the Tambo and Suretta nappes, two Brianconnais basement units at the eastern part of the Lepontine thermal dome (Fig. 1), were tectonically accreted to the Apulian upper plate some 47-50 Ma (SCHMID et al., 1996). In the Valais basin, sedimentation continued into Eocene time (LIHOU, 1995, 1996) when the basin finally closed and was subducted and accreted to the previously accreted European, Liguro-Piemontese and Apulian units making up the active margin (FROITZHEIM et al., 1996). This subduction involved HP metamorphism of crustal units as well as UHP metamorphism in upper mantle rocks (garnet-peridotites of Alpe Arami, Fig. 1 in ENGI et al., 2004; this vol.). Eclogite derived from oceanic crust of the Valais basin was initially dated at 36-43 Ma (localities at Alpe Arami and Gagnogne, BECKER, 1993, GEBAUER, 1996, 1999) but recent data from fragments in the VT unit on the main metamorphic structure map indicate a broader age range of about 35 to 55 Ma for this HP metamorphism (BROUWER et al., 2003a, b). These phase equilibria studies indicate that the rocks were exhumed rapidly from depths of more than 100 km to about 15-25 km, where they underwent Barrovian overprinting at 32 Ma. The exhumation of at least 75 km, possibly within a time as short as 3 Ma inferred from the minimum difference in ages between pressure- and temperature-dominated metamorphism in these units, was potentially very fast.

Engadin, Tauern and Rechnitz windows in the Eastern Alps

The Engadin, Tauern and Rechnitz windows expose folded and metamorphosed European, Valais and Liguro-Piemont units below a thrust contact with the overlying Austroalpine units. No attempts have been made so far to date HP metamorphism in the Engadin window. Certainly, this metamorphism is younger than the age of the youngest sediments (Late Cretaceous and Paleogene, OBERHAUSER, 1995). An Early Tertiary age is likely based on lateral correlation of the Valais and Liguro-Piemont units to the west.

Much more age data on metamorphism is available for the Tauern window, as reviewed in HOINKES et al. (1999) and, previous to that, in FRANK et al. (1987). Large parts of the European basement and its Paleozoic cover (Venediger nappe) as well as basal slices of the Tethyan ocean basin (Glockner nappe = Schistes Lustrés unit) experienced eclogite-facies metamorphism, overprinted by blueschist facies metamorphism. The baric peak was reached in Eocene time (ca. 45 Ma, CHRISTENSEN et al., 1994, ZIMMERMANN et al., 1994). In a detailed petrological and geochronological study of eclogitic garnets, CHRISTENSEN et al. (1994) determined that ages range from 35-55 Ma in the garnet cores to 30.5-32 Ma in their rims. The oldest reliable age for HP metamorphism in the Tauern window (62 Ma) was obtained by extrapolating back to the time of garnet nucleation with a calculated growth rate (CHRISTENSEN et al., 1994). Eocene/Oligocene (32-36 Ma) ages were obtained from $^{40}Ar/^{39}Ar$ studies of Si-rich phengites associated with blueschists in the Paleozoic cover (Lower Schieferhülle) of the European basement (ZIMMERMANN et al., 1994).

This places a minimum age on eclogitization, as the blueschist-facies metamorphism overprints the eclogites. DINGELDEY et al. (1997) reported 38-43 Ma $^{40}Ar/^{39}Ar$ ages for greenschist-facies phengites in the Valais unit (Upper Schieferhülle). Taken together, the data so far suggest that pressure-dominated metamorphism in the Tauern window occurred in Early Tertiary time, as expected from correlative lithotectonic units in the Central and Western Alps.

Temperatures during Tertiary, greenschist- to amphibolite-facies metamorphism peaked in Oligocene time (26-30 Ma, INGER & CLIFF, 1994; REDDY et al., 1993). The contoured Rb-Sr and K-Ar biotite cooling ages on the map delineate two thermal subdomes at each end of the Tauern window.

The contours in the western end are truncated by the overlying Brenner extensional fault, indicating that movement on this fault continued after cooling to below 300°C in the footwall (see also FÜGENSCHUH et al., 1997). Unfortunately, the temperatures achieved during this Tertiary overprinting metamorphism were insufficient to completely reset the Rb/Sr ages of pre-Tertiary white micas (REDDY et al., 1993), so that many of these ages may be mixed ages. In addition, the K-Ar system was affected to an unknown extent by excess Ar (CLIFF et al., 1985). The $^{40}Ar/^{39}Ar$ method would provided a means for controlling the amount of excess Ar, but investigations with this system are still rare in this area. The Rb-Sr and K-Ar mica ages reviewed in HOINKES et al. (1999) and FRANK et al. (1987) indicate that most of the cooling related to exhumation of the Tauern window occurred after 30 Ma in Oligocene to Miocene time. Muscovite ages (K-Ar, Rb-Sr) cluster at 21-30 Ma in the eastern Tauern window and at about 13 Ma and 15-24 Ma in western part. Rb-Sr and K-Ar biotite ages of 15-24 Ma occur in the eastern Tauern window.

The age map shows that the limit of Tertiary, temperature-dependent metamorphism corresponds to the Oligo-Miocene, DAV and Mölltal mylonitic faults (Fig. 1). The age map shows that the limit of Tertiary, temperature-dependent metamorphism corresponds to the Oligo-Miocene, DAV and Mölltal mylonitic faults (Fig. 1 and horizontal stripes at the southwest side of Tauern window on the age map). These strike-slip faults lie south of the southern boundary of the Tauern window as defined by the thrust contact between Austroalpine units and the underlying Penninic units. Recent structural studies (HANDY et al., 2004) have shown that in the Austroalpine crustal wedge between the Tauern window and the DAV fault, the main foliation was active during intrusion of the Rieserferner pluton (28-33 Ma, Rb-Sr white mica formational ages in MÜLLER et al., 2001) and overprints an earlier Alpine foliation of Early Tertiary (Müller et al. 2001) or Late Cretaceous age (BORSI et al., 1973; STÖCKHERT, 1984, discussion of dating methods in MANKTELOW et al., 2001). The DAV fault is therefore interpreted to have accommodated a significant exhumational component of N-side up motion, juxtaposing Alpine high-pressure, amphibolite facies assemblages in the north (STÖCKHERT, 1984) with Alpine-unmetamorphosed rocks in the south (SCHULZ, 1994) before becoming active as an Oligo-Miocene strike-slip fault (HANDY et al., 2004).

Exhumation of the Tertiary nappe pile in the Tauern window accelerated in Miocene time as manifested by T-t paths constructed with different mineral isotopic systems (Fig. 4 in DUNKL et al. 2003) and by sediment mass balance of the peri-Alpine basins (CLIFF et al., 1985; FRISCH et al., 1999). The distribution of zircon and apatite fission track (FT) ages suggest that exhumation of the eastern part of the Tauern window was slightly earlier (Zr ages: 16.3-21.5 Ma, DUNKL et al., 2003) than that of the western part (zircon mean age of 11.4 Ma, FÜGENSCHUH et al., 1997).

There are currently no reliable ages for the HP metamorphism in the Rechnitz window, although metamorphism was certainly younger than the youngest metamorphosed sediments (Lower Cretaceous) and no older than the youngest, unmetamorphosed sediments overlying the sequence (Miocene and Pliocene, PAHR, 1980). The overprinting greenschist-facies metamorphism is dated at 19-22 Ma by K-Ar muscovite (KOLLER, 1985). Zircon and apatite FT ages are, respectively, 13-22 Ma and 7-10 Ma (DUNKL & DEMENY, 1997). The average zircon FT age of 17.8 Ma is identical within error to the average age of 17.1 Ma in the eastern Tauern Window (DUNKL et al., 2003). These authors interpret the Tertiary exhumation of the Tauern and Rechnitz Windows to have been coeval. The poor exposure of the Rechnitz window has hampered efforts to find the structures associated with this exhumation and denudation.

Austroalpine units in the Eastern Alps

Recent isotopic age work in the Austroalpine nappes is reviewed in THÖNI (1999) and in SCHUSTER et al. (2004), so that only several points of contention are treated here. In the Silvretta-Seckau nappe system (Fig. 1), the line separating 60-110 Ma cooling mica ages from mixed, pre-Alpine and Alpine mica ages (ticked, dashed line in the age map) does not correspond everywhere with the metamorphic contact between sub-greenschist and greenschist facies. This reflects the resistence of the mica systems to resetting, even in parts of the nappe where temperatures in Late Cretaceous time approached 500°C. Similarly, Ar-Ar hornblende ages in the Seckau complex, part of the Silvretta-Seckau nappe system, are only reset where temperatures attained 500-600°C (FARYAD & HOINKES, 2003). Thus, some parts of the Silvretta-Seckau napppe system coloured light green in the age map may have experienced Late Cretaceous temperatures in excess of 300°C, at least for short times.

Late Cretaceous, sub-greenschist facies metamorphism in basement south of the Tauern window occurs in the lowest tectonic levels south of the large Tertiary faults marking the apparent southern limit of Alpine metamorphism (HOINKES et al., 1999). The light green colour of these units in the age map is based on the distribution of partially reset Rb-Sr biotite ages that indicate a mix between Late Cretaceous and pre-Alpine ages (DEUTSCH, 1988). The general weakening of metamorphism to anchizonal and diagenetic conditions with decreasing tectonic level in these basement units precludes an unequivocal determination of their metamorphic age. Similar problems are found in dating the low-grade metamorphism in the Northern Calcereous Alps.

Within parts of the Austroalpine basement that experienced HP-metamorphism, the pressure peak at about 100 ± 10 Ma (Sm-Nd garnet isochron ages, Ar-Ar white mica, review in THÖNI, 1999) was followed by overprinting under upper amphibolite-facies conditions at about 75 Ma (see cooling ages marked in blue on the age map). Tertiary metamorphism never attained 300°C in any of these units. In the Austroalpine basement southeast of the Tauern window, zircon FT ages increase away from the window from 30 Ma in the north to 160 Ma in the south (DUNKL et al., 2003). These authors attribute the trend to the superposition of Tertiary metamorphism onto an earlier thermal regime related to Jurassic (Tethyan) rifting. This weak Tertiary overprint decreases away from Tauern window. The lack of Neogene resetting of the FT ages is interpreted by DUNKL et al. (2003) to show that there was little or no exhumation associated with strike-slip motion during eastward lateral extrusion of the Austroalpine basement in Miocene time.

Southern Alps

Very low-grade metamorphism related to pervasive foliation and thrusting of the highest (Orobic) thrust sheet of the Bergamasc part of the Southern Alps (Fig. 1) is argued to be Late Cretaceous age, based on truncation of this thrust by the Early to Mid-Tertiary (29-43 Ma, DEL MORO et al., 1983) Adamello pluton (SCHMID et al., 1996). Another age constraint cited by COLOMBO & TUNESI (1999) is the occurrence of discordant 50-60 Ma dykes that truncate this foliation (K-Ar whole-rock ages, ZANCHI et al., 1990). For this reason, the southernmost limit of the light green colour in the age map of the Bergamasc Alps corresponds to the trace of the Orobic thrust. A later Alpine foliation in the basement and Mesozoic cover rocks seems to be younger than the Adamello granitoid intrusion (CARMINATI et al., 1997).

The extrapolation of this metamorphic age into the westernmost part of the Southern Alps (light green in the age map) is based on the correlation of S- and SE-directed thrusting and folding there with the structures in the Bergamasc Alps (SCHUMACHER et al., 1997). Although admittedly tenuous, this correlation is confirmed by the few available FT zircon ages in the Ivrea and Strona-Ceneri Zones (60-85 Ma, review in HURFORD et al., 1991). The occurrence of 15-30 Ma FT zircon and apatite ages adjacent to the Insubric mylonites along the Canavese fault (thin yellow domain in the age map, location in Fig. 1, HURFORD et al., 1991) is attributed to local reheating of the southern Alpine crust during Insubric backthrusting and exhumation in the retro-wedge of the Tertiary Alpine orogen.

Tectonic interpretations of the metamorphic age patterns

The most striking feature of the metamorphic age pattern is that Late Cretaceous ages (green shades) predominate in the Eastern Alps, whereas Tertiary ages (yellow-orange) are ubiquitous in the structurally deeper units of the Western Alps. Tertiary metamorphism in the Eastern Alps is restricted to the Lower Engadine Window, the Tauern Window and the smaller Rechnitz Window, between Vienna and Graz (Fig. 1). The separation of Late Cretaceous and Late Cretaceous-Tertiary metamorphism, respectively, in the Eastern and Western Alps, together with a similar pattern in space and time for flysch sedimentation (e.g., TRÜMPY, 1980) prompted SCHMID et al. (1996) to refer to the Alps as a composite mountain belt; a Jurassic-Late Cretaceous orogen in the east with the remains of a Triassic oceanic basin (Meliata-Halstatt) that rides "piggyback" on top of a Late Cretaceous to Tertiary orogen exposed in the west with the remains of two, Jurassic-Cretaceous oceanic basins (Valais and Liguro-Piemont). The remnants of the continental margins making up these orogens, as well as the basic rocks and marine metasediments marking the sutured ocean basins between them, are distinguished in Figure 2. From this figure, it is evident that in both orogens the limits of pressure-dependent metamorphism overlap with the lithotectonic boundaries between the upper and lower plates, and do not everywhere coincide with the oceanic sutures.

Pressure-dominated metamorphism

The 90-110 Ma ages of pressure-dominated metamorphism in the Eastern Alps (purple dots on the map) are interpreted to date east-southeastward subduction of a part of the Middle Triassic, Austroalpine passive margin beneath distal parts of the same margin to the east. Figure 2 shows that the pressure-dominated metamorphism is far from the nearest fragments of the Middle

Triassic, Meliata-Hallstatt ocean basin, exposed in mélanges within the Juvavic nappes of the Northern Calcereous Alps (MANDL & ONDREJICKI, 1991; KOZUR & MOSTLER, 1992). Prior to Late Cretaceous time, this ocean basin was located to the east, between the Austroalpine and Tisian continental margins (NEUBAUER, 1994; FROITZHEIM et al., 1996) and is best exposed in the northwestern Carpathians. Closure of a westward embayment of the Meliata-Halstatt basin in the Eastern Alps is manifested by Late Jurassic thrusting in the Juvavic units (Hallstatt mélange of FRISCH & GAWLICK, 2003), earlier than 90-110 Ma subduction and HP-metamorphism of the Austroalpine units. This spatial and temporal discrepancy has fueled considerable debate, as recently discussed in FROITZHEIM et al. (1996) and MILLER & THÖNI (1996). Because the Mid-Triassic passive margin sequence in the NCA was originally situated north and/or east of the Austroalpine basement (e.g., FRISCH & GAWLICK, 2003), Jurassic to Cretaceous shortening that culminated in 90-110 Ma subduction must have migrated from east to west, away from the Meliata-Hallstatt suture and into the lower plate (FROITZHEIM et al., 1996). Thus, the Eastern Alps do not contain the upper plate to this suture and the boundary marked in Figure 2 is the base of the overthrusted hangingwall to the HP rocks within the lower (Austroalpine) plate margin.

The anomalous position of 90-110 Ma HP- and even UHP-metamorphism within the formerly passive, Austroalpine margin (e.g., MILLER & THÖNI, 1996) may reflect the localization of subduction within a Late Paleozoic/Early Mesozoic rift system, manifested by the Permian age of gabbroic relics in Late Cretaceous eclogites (e.g., Koralpe eclogites, MILLER & THÖNI, 1997; THÖNI & MILLER, 2000). An alternative view that the 90-110 Ma eclogites mark the northern or western branch of another sutured ocean basin (e.g., the Vardar basin in the Dinarides, or a "southern Tethyan" ocean, KOZUR & MOSTLER, 1992) is considered less likely due to the lack of pelagic sediments associated with the high-pressure rocks.

Pressure-dominated metamorphism in the Western and Central Alps (35-90 Ma, red and blue dots in the age map) is younger than in the Eastern Alps and partly overprints the imbricated remnants of the Valais and Liguro-Piemont basins as well as their adjacent European and Apulian margins (Fig. 2). These oceanic basins were located west of the Meliata-Hallstatt suture (FROITZHEIM et al., 1996) and opened as the latter basin was closing in Jurassic to Cretaceous time. East-southeastward subduction of the Liguro-Piemont oceanic basin initiated at 100-120 Ma, as recorded by flysch and mélange with ophiolitic and high P/T detrital minerals (e.g., WINKLER, 1988; WAGREICH, 2001). Then, distal parts of the upper-plate continental margin were subducted, as evidenced by 60-90 Ma pressure-dominated metamorphism in the Lower Austroalpine units of the Eastern and Western Alps (blue dots on the age map). Subsequent migration of subduction into the footwall is indicated by 35-60 Ma HP- and UHP-metamorphism in the Liguro-Piemont and European units (red dots on the map). This NW migration of subduction (e.g., GEBAUER, 1999) is consistent with the younging of Tertiary flysch ages in progressively more external European units that escaped metamorphism (e.g., SCHMID et al., 1996 and references therein). The aforementioned occurrence of Late Cretaceous to Early Tertiary, pressure-dominated metamorphic ages in Austroalpine units of the Western Alps is attributed to progressive subduction and imbrication of extensional allochthons of the Apulian, upper plate margin that were situated in the southeastern part of the Liguro-Piemont ocean basin (DAL PIAZ et al., 2001). Exhumation of the HP metamorphic units also appears to have migrated to the NW behind the subduction zone (WHEELER et al. 2001), as manifested by spatial variation in mica cooling ages from 40-60 Ma in the Sesia Zone to 35-28 Ma in the more external Liguro-

Piemont and European basement units. Several mechanisms have been proposed for the exhumation of these HP rocks, including the extrusion of thin, basement nappes within the subduction channel (SCHMID et al., 1996; ESCHER & BEAUMONT, 1997). However, it is unlikely that all, or even most, of the exhumation involved extensional faulting in the hangingwall of the subduction zone as proposed by WHEELER et al. (2001), because retrograde metamorphism in the footwall of extensional faults observed so far never exceeded upper greenschist-facies conditions. The mechanisms by which HP rocks were exhumed is the subject of ongoing work.

If pressure-dependent metamorphism is taken as a marker for Alpine subduction, then the boundaries of Alpine subduction in Figure 2 are neither easily defined nor everywhere clearly exposed in the field. This is due to the migration of subduction and collision, as well as to the overprinting of HP assemblages during temperature-dominated metamorphism and multistage exhumation. In the Eastern Alps, for example, both Late Cretaceous and Oligo-Miocene oblique-slip tectonics have severely segmented the Jurassic-Cretaceous, Austroalpine margin adjacent to the sutured Meliata-Hallstatt ocean (e.g., FRISCH & GAWLICK, 2003). The southern border of 90-110 Ma pressure-dominated metamorphism within this margin is the southern border of Tertiary, Alpine metamorphism marked by reactivated, Oligo-Miocene mylonitic faults (e.g., the DAV, Mölltal and Karawanken faults, Fig. 1). In the Western and Central Alps, it is difficult, if not actually impossible, even to consider Late Cretaceous to Tertiary subduction in terms of a channel. Part of the limit of 60-90 Ma, pressure-dominated metamorphism in the Apulian upper plate is truncated to the south by the Canavese segment of the Periadriatic fault system (Fig. 2). The northward extent of Late Cretaceous HP metamorphism in the footwall is overprinted by Eocene, pressure-dominated metamorphism in the Liguro-Piemont and European basement units. In turn, this Early Tertiary, HP-metamorphism is delimited to the north and west by the multiply folded contact of the European (Briançonnais) basement with the Valais oceanic unit. In the Western Alps, the lower limit of Eocene subduction for the Valais basin and adjacent European margin is truncated by the Miocene Penninic frontal thrust (Fig. 2), whereas in the Central Alps, it corresponds with the boundary of the ultrahelvetic metasediments (cover of the Gotthardmassif) lacking traces of HP metamorphism and the HP metamorphic Schistes Lustrées of the Valais basin. In the Lepontine thermal dome, a narrow unit marked VT on the main metamorphic structure map contains variegated continental and oceanic lithologies with HP and HT parageneses; these are interpreted as mélange relics within a tectonic accretionary channel (TAC of ENGI et al., 2001). This putative channel formed within a broader zone of subduction that included parts of the adjacent European margin.

Temperature-dominated metamorphism

Temperature-dominated metamorphism post-dated the stacking of most basement nappes in the Alps, as shown by the fact that basement nappe contacts are usually cut discordantly by metamorphic facies contacts and cooling age contours. This is most obvious for the Tertiary, temperature-dominated metamorphism of the Lepontine and Tauern thermal domes (red cooling age contours on the map). However, it also pertains to Late Cretaceous metamorphism of the Eastern Alps (blue cooling age contours on the map) as well as to Tertiary metamorphism of other internal basement units in the arc of the Western Alps. In fact, most basement thrusting and nappe stacking occurred during the accretion-subduction stages of Alpine metamorphism, before the attainment of peak temperatures. Temperature-dominated metamorphism is therefore related to the syn- to late-collisional stages of the two Alpine tectonometamorphic cycles outlined above.

In the Koralpe and Saualpe basement units (Fig. 1), exhumation of 90-110 Ma HP units involved coeval top-N to –NW thrusting under upper amphibolite-facies conditions in the footwall and top-SE extensional faulting above (RATSCHBACHER et al., 1991, see ages in FRANK et al.. 1983). The mica cooling ages in this area (70-80 Ma blue ages and contours in the age map) cut across the nappe contacts. SCHUSTER et al. (2004) attribute younger mica cooling ages (70-75 Ma, THÖNI, 1999) further to the south as the result of later backfolding in the retro-wedge of the Late Cretaceous orogen. In the Öztal complex and Silvretta unit (Fig. 1), retrograde amphibolite-to-greenschist facies metamorphism at about 70-90 Ma is well exposed in the footwall of low-angle normal faults that accommodated top-E displacement of the hangingwall along reactivated, E-dipping nappe thrusts (RATSCHBACHER et al., 1989, e.g., the Schlinig fault in FROITZHEIM et al., 1997). This extensional deformation is interpreted to have exhumed and cooled the Austroalpine basement nappes to below 300°C some 70-90 Ma, i.e., within 30 Ma or less of W-directed thrusting at near-peak temperatures (see discussion on pp. 218-219 of THÖNI, 1999).

In the Lower Austroalpine Err-Bernina complex (Fig. 1), extensional exhumation may have occurred simultaneously in the hangingwall of thrusting and subduction. Thrusting and accretion under HP-greenschist facies conditions at 76-88 Ma overlapped with extensional deformation under lower pressure, greenschist facies at 67-80 Ma, by which time subduction had migrated westwards into the Liguro-Piemont oceanic domain (HANDY et al., 1996). HANDY (1996) proposed extensional exhumation of the accreted Austroalpine, continental margin behind the westwardly retreating hinge of the Tethyan subduction zone.

Thrusting post-dated metamorphism in the thrust-and-fold belts of the Alpine fore- and hinterlands, where there are several well-documented examples of transported metamorphism in the hanging wall of thrust sheets (e.g., Glarus thrust in the Helvetic nappes, HUNZIKER et al., 1986; PFIFFNER, 1993; RAHN & GRASEMANN, 1999) that root in basement thrusts in their hinterlands (e.g., SCHMID et al., 1996; TRANSALP working group, 2002). Most of these examples of transported metamorphism are too small to depict on the Map of Metamorphic Structure in the Alps, the notable exceptions being Tertiary, low-grade metamorphism in thrust sheets of the Préalpes Romandes (Fig. 1, BOREL, 1991) and Late Cretaceous, sub-greenschist metamorphism in the hangingwall of the Orobic thrust in the Bergamasc part of the Southern Alps (SCHUMACHER et al., 1997).

The arcuate to concentric, Tertiary biotite cooling age contours in the Lepontine and Tauern thermal domes reflect exhumation of the Penninic basement nappes along various segments of the Periadriatic fault system (Fig. 1). This fault system and related post-nappe folds formed at about 35 Ma to 10-15 Ma, a period that ARGAND (1916) and many others since have referred to as the Insubric Phase. Insubric deformation substantially modified the Alpine orogenic edifice in response to tectonic indentation by the cold and therefore rigid, southern Alpine lithosphere. The map in Figure 1 shows the southern Alpine indenter and the Periadriatic fault system. Insubric deformation occurred under mostly mylonitic, retrograde amphibolite- to greenschist-facies conditions, but continued under brittle, sub-greenschist facies conditions in late Miocene time (SCHMID et al., 1996).

In the case of the Lepontine dome, exhumation involved a combination of S-directed thrusting and folding along the steeply N-dipping, Tonale segment of the Insubric mylonite belt (Fig. 1, SCHMID et al., 1989), and NE-SW directed, orogen-parallel extension along the Simplon, Forcola and Turba low-angle normal faults at either end of the dome (GRASEMANN & MANCKTELOW, 1993, MEYRE et al., 1998). Similarly, exhumation of the Tauern dome initiated at its southern margin along the conjugate DAV and Mölltal mylonitic faults, and ended along the Brenner and Katschberg extensional faults (Fig. 1, HANDY et al., 2004). Faulting was broadly coeval with the development of large (km-amplitude), upright folds in the basement core of the domes (HANDY et al., 2004). These folds have a strong component of stretching parallel to their axes and deformed the cooling age contours for the Rb-Sr white mica and biotite systems in the Lepontine (STECK & HUNZIKER, 1994) and Tauern (CLIFF et al., 1985; REDDY et al., 1993) thermal domes, as shown in the age map. This suggests that folding continued to below 500°C and possibly to below 300°C, the temperatures commonly cited for the closure to diffusion of the Rb-Sr systems in white mica and biotite, respectively (von BLANKENBURG et al., 1989). In this context, it is interesting to note that Insubric exhumation and cooling of the Lepontine thermal dome in the core and retro-wedge of the Central and Western Alps was coeval with N- and NW-directed thrusting of the weakly metamorphosed Helvetic units towards the northern Alpine foreland (e.g., the Glarus thrust, SCHMID et al., 1996).

The Lepontine and Tauern thermal domes have been likened to metamorphic core complexes (e.g., FRISCH et al., 2000), but this comparison is somewhat misleading from a structural standpoint; unroofing of the basement rocks in the classical core complexes of North America involved low-angle normal faulting during regional extension (e.g. CRITTENDEN, 1980), whereas exhumation of the Lepontine and Tauern thermal domes was syn-orogenic in the retro-wedge of the Alpine orogen. It involved a combination of south-directed thrusting ("backthrusting”, "Rücküberschiebung” or "retrocarriage” in Alpine parlance) and strike-slip faulting in addition to orogen-parallel, low-angle normal faulting.

We note that our division of Alpine metamorphic ages into two pressure- and temperature-dominated cycles does not completely correspond to TRÜMPY´s (1980) well-known division of Alpine orogenic history into Eo-Alpine, Meso-Alpine and Neo-Alpine phases. These phases were based largely on age relationships between deformation and sedimentation. Although the 90-110 Ma HP-metamorphism in the Eastern Alps indeed coincides with the Eo-Alpine phase in the sense of TRÜMPY, 35-60 Ma and 60-90 Ma HP-metamorphism in the Western Alps was not regionally recognized when TRÜMPY proposed his orogenic phases. Early Tertiary, pressure-dominated metamorphism overlaps in time with his Meso-Alpine phase which is centered in the Penninic domain. TRÜMPY´s Neo-Alpine phase involved Miocene to Pliocene folding and thrusting, together with intracrustal subduction along the southern border of the External basement massifs. Since the 1970s, however, structural work has shown that the External massifs were not the site of subduction, and were uplifted to their present altitude in Miocene to Pliocene time (BURCKHARD, 1988, LE LOUP et al., 2004), i.e., at about the same time as folding and thrusting in the unmetamorphosed Jura mountains.

Final remarks

The new map of the age and structure of Alpine metamorphism comes close to realizing an old idea of Hans Stille, recently revived by HSU (1995), of integrating tectonic and metamorphic information in a tectonometamorphic facies map for an entire orogen. Such a map is useful from a geodynamic standpoint because it combines information about P-T-X conditions in the orogenic crust with information about the structure and timing of orogenic deformation. The map therefore serves as a basis for reconstructing the tectonic and dynamic evolution of an orogen, especially when combined with geological maps on the same scale.

As the example of the Alps shows, structures and metamorphism are closely linked in a positive feedback loop: Metamorphic phase transformations enhance strain localization by changing the rheology of the crust. The heterogeneous structure resulting from strain localization in turn affects the distribution of metamorphism and the susceptibility of the crust to further deformation. Strain-induced heterogeneities associated with Mesozoic rifting and with subsequent subduction were the structural template on which the architecture of the Alpine orogen formed. Modifications to this structure occurred during exhumation, especially when the Periadriatic fault system segmented large tracts of metamorphosed crust. This fault system also accommodated the upward advective flow of fluids and granitic melts. Boundaries between first-order tectonic units like lithospheric plates therefore rarely coincide exactly with the boundaries between metamorphic facies domains. Rather, the distribution of these domains is usually related to the fabric developed during orogenic deformation.

Finally, a map like this is useful not only because it summarizes what we think we understand about crustal evolution, but also because it indicates where data are lacking or insufficient to draw firm conclusions. Use of the Alps as a natural laboratory to test ideas on crustal processes, for example, the causes of seismicity, or on the effect of climate on tectonics, will continue to depend on obtaining a dense distribution of radiometric ages. Future research will undoubtedly focus on the application of high-resolution, in-situ dating techniques to obtain ages of minerals within a well-established structural and petrological framework.

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