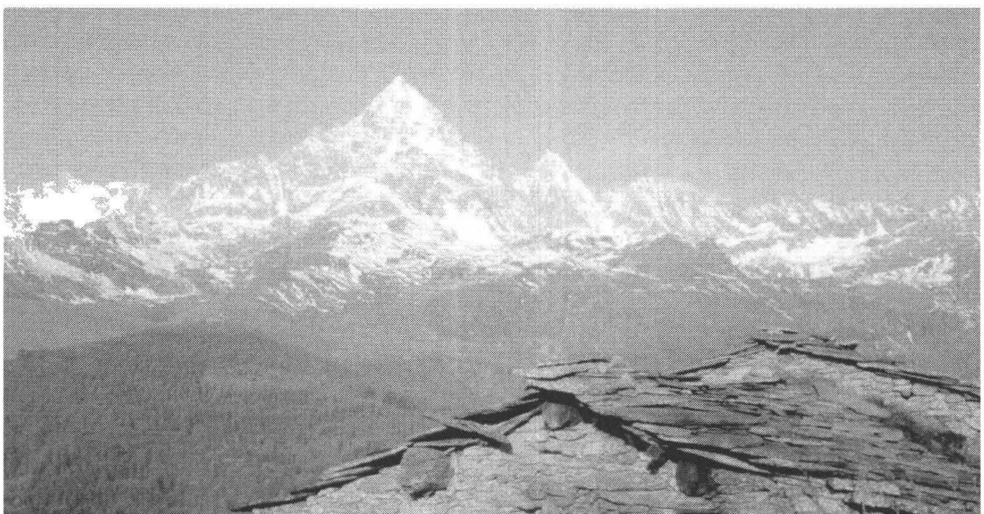
Explanatory Notes to the Map

METAMORPHIC STRUCTURE OF THE ALPS

(Roland Oberhänsli, Editor)



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EXPLANATORY NOTES TO THE MAP: METAMORPHIC STRUCTURE OF THE ALPS INTRODUCTION

by

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Abstract

Two new maps describing the Mesozoic-Cenozoic, Alpine metamorphic structure (1:1'000'000) and metamorphic ages (1:2'000'000) are presented. A short discussion of the map units used is provided to introduce some key papers summing up new ideas, lines of thought, the data used and the problems encountered.

General remarks

These maps and notes are based on studies of Austrian, French, Italian and Swiss earth scientists who worked in the Alps for the last 30 years, trying to understand the Mesozoic and Cenozoic evolution of the orogen. We investigated the Cretaceous and Tertiary closing of the Tethyan realm, subduction related processes, and the exhumation of the Alps. Most data have been published in specialized journals, others are the result of recent investigations of our working groups.
Concise compilations of recent geophysical data have been published from ECORS-CROP (ROURE et al., 1990; DAL PIAZ et al., 2003) and NRP20 (BLUNDELL et al., 1992; PFIFFNER et al., 1997) for the Western and the Central Alps. Results from the Eastern Alps are about to be published (TransAlp, 2002). A new compilation is given by SCHMID et al. (2004b). These studies resulted in a better knowledge of the present deep structure documenting subducted remains of passive margins and a distinct variation along strike in the deep structure of the Alpine orogen. These results added substantially to the pioneering ideas of geologists during the last century (ARGAND, 1911, 1916, 1924, 1934; AMPFERER, 1906; BERTRAND, 1884; FRANCHI et al., 1908; HEIM, 1919-22; LUGEON, 1902; LUGEON & ARGAND, 1905; STEINMANN, 1905; TERMIER, 1904) who conceived and developed the nappe theory from the cover to the basement nappes throughout the Alps (historical review in DAL PIAZ, 2001).

ELLENBERGER (1958), TRÜMPY (1960) and TOLLMANN (1963) gave further advances in stratigraphy, regional tectonics and paleogeographic reconstructions. DAL PIAZ (1928) gave one of the earliest modern works on Alpine eclogites and glaucophane-bearing rocks. ERNST (1971), DAL PIAZ (1971) and DAL PIAZ et al. (1972) innovated the interpretation of HP metamorphism in the Alps. Further compilation were presented by SPALLA et al., (1996) and GODARD (2001).
As the map of the distribution of metamorphic rocks of the Alps compiled by the late Martin Frey and co-workers did not account for tectonic setting and geodynamic evolution, our initial objective was to show differences in the geodynamic evolution of various parts of the Alpine orogen. To do so, we should have included kinematic information based on structural and paleomagnetic data, as well as the age and distribution of flysch sequences, much of which has been published over the last thirty years. The regional distribution of such data, however, is quite uneven and would have hampered the readability of the map, hence we decided to concentrate on the type and grade of the metamorphism. To the extent that metamorphism is related to geodynamic processes, our new maps show which units underwent which process, approximately at what time and to what depth. We made the choice to refer to conditions where pressure and temperature peak were reached simultaneously or where a temperature peak was reached at lower pressures after a significant temperature increase during the decompression path (hatched areas). These choices at the first glance clearly show what type of process is linked the main metamorphic structure: subduction process as for the Western Alps or collision process for Central Alps, and complex metamorphic structures as in the Eastern Alps being due to a complex geodynamic and metamorphic history involving the succession of the two types of process. The new maps show where subduction-, collision-, exhumation-related types of metamorphism are found in the Alps. The FREY et al. (1999) map was an obvious and excellent starting point for this task.

In addition we are working on an interactive CD version of the maps, presenting information on the data used for this compilation. Our working philosophy is explained in the chapter Extended Legend and in the regional compilations that follow.

Since the aim of these maps is to address the Mesozoic-Cenozoic evolution of the Alps, all pre-Alpine metamorphic features have been omitted. Highlighting domains overprinted by Alpine "peak" metamorphic reactions typical for certain geotectonic settings results in a picture much easier to read than previous maps of the metamorphic evolution of the Alps published by NIGGLI & NIGGLI (1965), NIGGLI & ZWART (1973), ZWART et al. (1973, 1978) and FREY et al. (1974, 1999), which all strive to emphasize polymetamorphic and/or plurifacial complexities. Our new map shows Alpine metamorphic peak conditions irrespective of when these were attained. The age information is given in a separate map shown as inset (1:2'000'000). We also added new data, notably compiled from high-pressure metamorphic metapelites. Thus the wide distribution of subduction related metasediments of the Valais ocean domain have brought forth new geodynamic aspects and paleogeographic reconstructions.

Fig. 1 shows local names used in the text but partly omitted on the metamorphic map and the position of the main Jurassic paleogeographic elements within the Mid- to Late Tertiary structure of the present Alps; it also indicates major metamorphosed fault zones. Although our metamorphic map tries to show a general picture of the Alpine thermo-mechanical evolution, this could not be done without reference to local names. To maintain clarity on the metamorphic map and as thesaurus for the "non-Alpine" reader we used a modified version of the tectonic map by SCHMID et al. (2004a). The map of SCHMID et al. (2004a) is based on the structural model of Italy (BIGI, et al., 1989, 1990a, 1990b, 1992).

The metamorphic map clearly shows a relatively simple picture for the Western Alps with an internal high-pressure dominated part thrust over an external greenschist to low grade domain, although both metamorphic domains are structurally very complex (GOFFÉ et al., 2004 this volume; BOUSQUET et al., 2004, this volume). 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 for subduction (and partial accretion) followed by an intensely evolved collision process resulting to an heating event during the decompression path of the early subducted units (hatched units in the map) (ENGI et al., 2004, this volume). Subduction-related relics and (collisional/decompressional) heating phenomena in different tectonic edifices characterize the Eastern Alps (Schuster et al., 2004, this volume). This complex picture is due to a dual Cretaceous and Tertiary metamorphic evolution related to a complex tectonic history. For the Tuscan and Corsica parts of the map the reader is invited to see the synthetic work of JOLIVET et al. (1998) that was used as reference to draw this part of the map.

Legend of the metamorphic structure map

The following divisions were used as legend on the map

LGM **Low grade metamorphism**

DIA: Diagenesis / sub-anchizone **(T < 200°C; P < 0.3 GPa)**
zeolite / illite – kaolinite

SGS: Sub-greenschist facies **(T 200–300°C; P < 0.5 GPa)**
laumontite – prehnite – pumpellyite / kaolinite – chlorite – illite – interlayered illite – smectite

GS **Greenschist facies**

LGS: Lower greenschist facies **(T 300–450°C; P < 0.7 GPa)**
albite – chlorite – epidote ± actinolite / albite – chlorite – phengite / pyrophyllite – chlorite– illite – phengite – paragonite ± chloritoid

UGS: Upper greenschist facies **(T 420-500°C; P < 0.8 GPa)**
actinolite / biotite – chlorite – kyanite ± chloritoid

HPGS: High-pressure greenschist facies **(T 300–450°C; 0.6 < P < 1.0 GPa)**
albite – lawsonite – chlorite ± crossite / phengite – chlorite ± chloritoid ± kyanite

GAT **Greenschist- amphibolite transitional facies** **(T 450–600°C; 0.8 < P < 1.2 GPa)**
albite – epidote – amphibole / biotite – garnet – chloritoid / phengite – chloritoid – kyanite

AM **Amphibolite facies** **(T 500–650°C; 0.5 < P < 1.3 GPa)**
plagioclase – hornblende – garnet / biotite – garnet – staurolite – phengite ± kyanite

BS **Blueschist facies**

BS: Blueschist facies **(T 250–400°C; $0.8 < P < 1.5$ GPa)**

glaucophane – lawsonite – jadeite – quartz /Fe-Mg-carpholite – phengite ± pyrophyllite ± chloritoid

UBS:Upper blueschist facies **(T 380–5s50°C; $1.0 < P < 1.5$ GPa)**

glaucophane – epidote – garnet / chloritoid – glaucophane – phengite ± garnet

BET **Blueschist to eclogite transitional facies** **(380–550°C; $1.3 < P < 1.8$GPa)**

blue amphibole – zoisite – garnet ± clinopyroxene / garnet – Mg–rich chloritoid – phengite

ECL **Eclogite facies** **(T 450–750°C; $1.3 < P < 2.5$ GPa)**

garnet – omphacite – zoisite – quartz ± amphibole ± phengite / garnet – Mg–rich chloritoid – kyanite – phengite / garnet – lawsonite

UHP **Ultrahigh-pressure facies** **(T 600–800 °C; $2.5 < P < 4.0$ GPa)**

garnet – omphacite – coesite – zoisite / Mg–rich chloritoid – talc – phengite – kyanite – pyrope – coesite

VT **Variegated HT facies** **(T 600–800°C; $0.7 < P < 2.5$ GPa)**

Tectonic mélange with relics of ECL, AM, and local granulite facies, interpreted as tectonic accretion channel (TAC); in the Southern Steep Belt evidence of partial melting is widespread

These divisions are based on metamorphic assemblages identified in mafic and in pelitic compositions. Temperature and pressure limits for different facies are far from being precisely defined but represent a compromise for different rock compositions. Sketches of P-T grids give the P-T pathes used to define the P-T grid shown in the map..

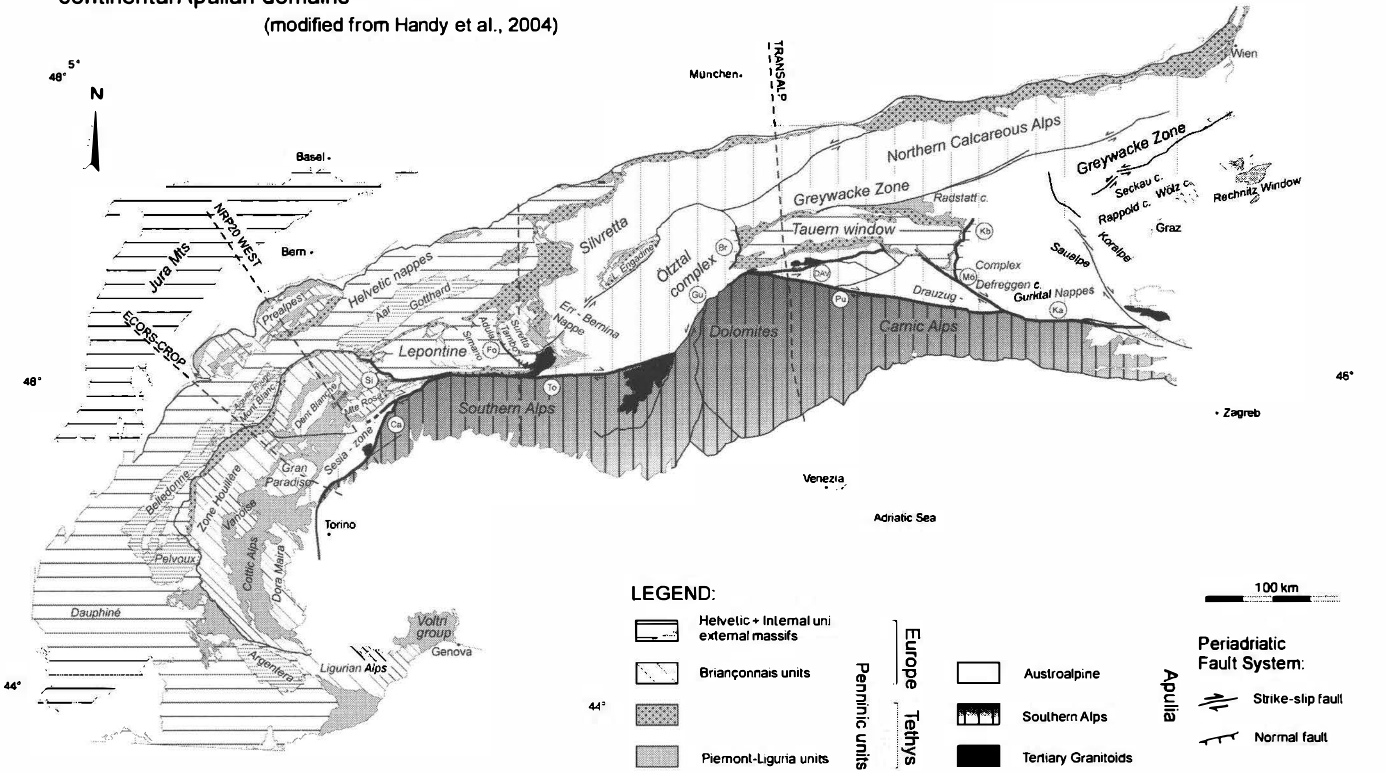
Large parts of the Austroalpine unit consist exclusively of pre-Alpine metamorphic rocks over-printed during the Eo-Alpine event at various grade. In these rocks the prograde assemblages defined above can not be recognised, but the following criteria have been used to cover the area:

LGM	(low grad metamorphism)	
	diagenesis / sub anchizone	illite cristallinity and coalification data
	sub greenschist facies	illite cristallinity and coalification data
LGS	~ 300 °C	total reset of Rb-Sr isotopic system in biotite
UGS	~ 400 °C	total reset of K-Ar isotopic system in muscovite
GAT	~ 500 °C	garnet-in, assemblage Ms + Ca-amphibole
AM	~ 600 °C	staurolite-in

As far as sub-anchi facies (DIA), sub-greenschist facies (SGS), lower greenschist facies (LGS), upper greenschist facies (UGS) and high-pressure greenschist facies (HPGS) are concerned, these facies terms as well as the corresponding P and T conditions can be considered as standard. The transitional greenschist amphibolite facies (GAT) accounts for the fact that different bulk rock compositions either produce greenschist or amphibolite facies mineral assemblages within this pressure and temperature realm.

No Eo-Alpine blueschist facies rocks are reported from the Austroalpine units.

Fig. 1: **Simplified tectonic map of the Alps**
indicating regional names and showing:
continental European, oceanic Tethyan and
continental Apulian domains
(modified from Handy et al., 2004)



Mylonitic amphibolite - greenschist facies fault zones

(Ca) Canavese (To) Tonale (Gu) Giudicaria (Pu) Pustertal (Ka) Karawanken

(Si) Simplon (Fo) Forcola (Br) Brenner (DAV) Deferregen-Antholz-Vals (Mö) Mölltal Katschberg

Instead the collision-related pressure-dominated rocks between greenschist facies and eclogite facies re-equilibrated in the GAT field. For some areas clear amphibolite facies (AM) conditions are evident in the field. Blueschist facies rocks can be divided into normal blueschist facies (BS) rocks and garnet-bearing blueschists that experienced somewhat higher temperatures and are classified as upper blueschist facies (UBS) rocks. For the transition from blueschist to eclogite facies, where all intermediate stages can be found in various tectonic units, we chose to lump the different rock types in a blueschist to eclogite transitional facies (BET). The eclogite facies is subdivided into eclogite facies (ECL) and ultrahigh-pressure facies (UHP), based on the quartz – coesite phase transition. In the southern part of the Central Alps rocks occur that apparently underwent different metamorphic conditions within coherent tectonic units. As these outcrops are to small to be mapped, the composite zone has been interpreted as remnant of a tectonic accretion channel (see below). In order to avoid a tectonic term in the legend, we summarize all rocks exhibiting amphibolite, eclogite or granulite facies metamorphism, as well as migmatization (in the Southern Steep Belt) under the term variegated high temperature facies (VT).
The colour code applied to the metamorphic facies domains indicates subduction-related metamorphic conditions by blue, pink and violet tints. Yellow, green to red colours indicate conditions related to continental collision. Red to orange tints suggest high temperature conditions, which appear to be related to exhumation (e.g. TAC, see ENGI et al., 2004.).

Legend of the Alpine tectono-metamorphic age map

The choices made for the presentation of metamorphic ages is discussed by HANDY & OBERHÄNSLI (2004, this volume).
High-retentivity isotopic systems such as Sm-Nd, Hf-Lu of HP assemblages and U-Pb SHRIMP data of zircon were used to assess ages of high-pressure metamorphism. Rb-Sr, Ar-Ar and K-Ar biotite and white mica cooling ages were used to separate areas dominated by cooling ages from areas where mixed ages are observed. For some areas biotite cooling ages were contoured to show the cooling pattern of the thermal overprint.
Green and yellow-orange colours indicate, respectively, the Cretaceous and Tertiary metamorphic cycle. Dotted areas show tectonic units that experienced high-pressure metamorphism.

Conclusions

These maps include information based on recent data from high-pressure metasediments that yields new aspects of the geodynamic evolution of the Alps. The fact that subduction-related high-pressure metamorphism can be identified all along the Valais ocean domain calls for adapted paleogeographic reconstructions.
The compilation of this new map resulted in two aspects. In our opinion, the Mesozoic and Tertiary evolution of the Alps has been depicted in a way permitting an easier approach to a geodynamic understanding of this orogen.

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EXPLANATORY NOTES TO THE MAP: METAMORPHIC STRUCTURE OF THE ALPS WESTERN AND LIGURIAN ALPS

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1 - Generalities and choice for the representation

In the Western and Southwestern part of the Alps from Val d'Aoste in the North to Genova in the South, the Alpine Type Metamorphism, characterized by a high-pressure low-temperature regime (HP-LT), is particularly well expressed.
In this area, the retromorphic conditions influencing the rocks during their exhumation paths have never exceeded the temperatures attained at peak pressure. As a result, during decompression of the metamorphic rocks the PT-t trajectories always remained cooling paths. Therefore, our choice was to represent the metamorphic peak conditions, while the retromorphic evolutions are only indicated together with ages in the inset map and not on the main map. However, these retromorphic imprints exist and can be locally intense.

2 - The main metamorphic zones

In the area of the Western Alps the HP-LT conditions range from the very low-grade greenschist facies to the Ultra High Pressure (UHP) conditions crossing 8 of the 14 metamorphic facies encountered in the whole map.
Generally the contacts between the metamorphic units correspond to tectonic contacts (thrusts, normal faults, strike-slip faults). However, on the map, the boundaries between the metamorphic units frequently appear as crossing the tectonic contacts mainly when they correspond to the limits of paleogeographic domains.

Detailed examination of these contacts shows that this feature is the result of the late tectonic evolution bringing into contact units of equal metamorphic grade but different ages. Two main examples of this feature can be found in the blueschist and in the eclogite facies zones that overlap both oceanic (Schistes Lustrés nappe) and continental (Briançonnais and internal basements) domains: the high pressure metamorphic conditions prevailing in the Briançonnais domain and in the internal basements are Late Tertiary in age (Oligocene) while in the oceanic domain these conditions are Early Tertiary in age (early Eocene) (DUCHENE et al, 1987; AGARD et al. 2002).

Despite the simplistic choice of the metamorphic criteria, only oriented on the metamorphic peak conditions and thus related to early orogenic processes (subduction), the metamorphic imprint at the map scale is consistent with the geometry of the Western alpine arc, i.e. the PT metamorphic conditions increase from the external to the internal part of the arc with an inward movement of the subducting slab. However, more complex situations resulting from the initial structure of the European or Apulian margins or resulting of the late tectonic of the belt can be depicted. Two main examples of this situation are particularly interesting to be mentioned (see also the general cross section of the Western Alps shown in Figure 1):

1) The repetition of the metamorphic sequence (greenschist-blueschist-eclogite facies) observed in the Northwestern part of the Alps from the external to internal basements through the Valaisan, the Briançonnais and the Ligurian domains. This can be related to the prolongation of the southern realm of the Valaisan oceanic domain;
2) The decrease of the metamorphic grade in the deepest part of the belt, i.e. the easternmost side of the Dora Maira internal basement, with a reappearance of HT blueschists facies conditions in the Pinerolo unit below the overlying eclogitic units. This metamorphic structure can be interpreted as the result of the late tectonic evolution of the orogenic wedge.

The nature of some boundaries of the metamorphic facies is still not totally determined. Some boundaries run along isograds as for the appearance of the very low-grade metamorphism in the external part of the belt or as for the external limit of the HP greenschist facies in the Briançonnais domain, North-West of Briançon. Some could be undefined tectonic contacts as for the Blueschist - Upper Blueschist facies limits in the Schistes Lustrés nappe in the Cottian Alps, East and South-East of Briançon.

The HP-LT metamorphic conditions occur in all rocktypes encountered in the belt including continental basements, oceanic crust and an exceptional variety of metasediments. Generally, the PT conditions recorded by the different rocktypes are consistent. Only in two specific areas of the Schistes Lustrés domain, West of the Gran Paradiso and West of the Monviso, the metamorphic imprint of mafic blocks or slices contrasts with the surrounding pelitic lithologies. This is represented, on the map, by coloured dots superposed on the main metamorphic facies. These features suggest the possible existence of a melange of high grade metamorphic blocks in a matrix of lower metamorphic degree.

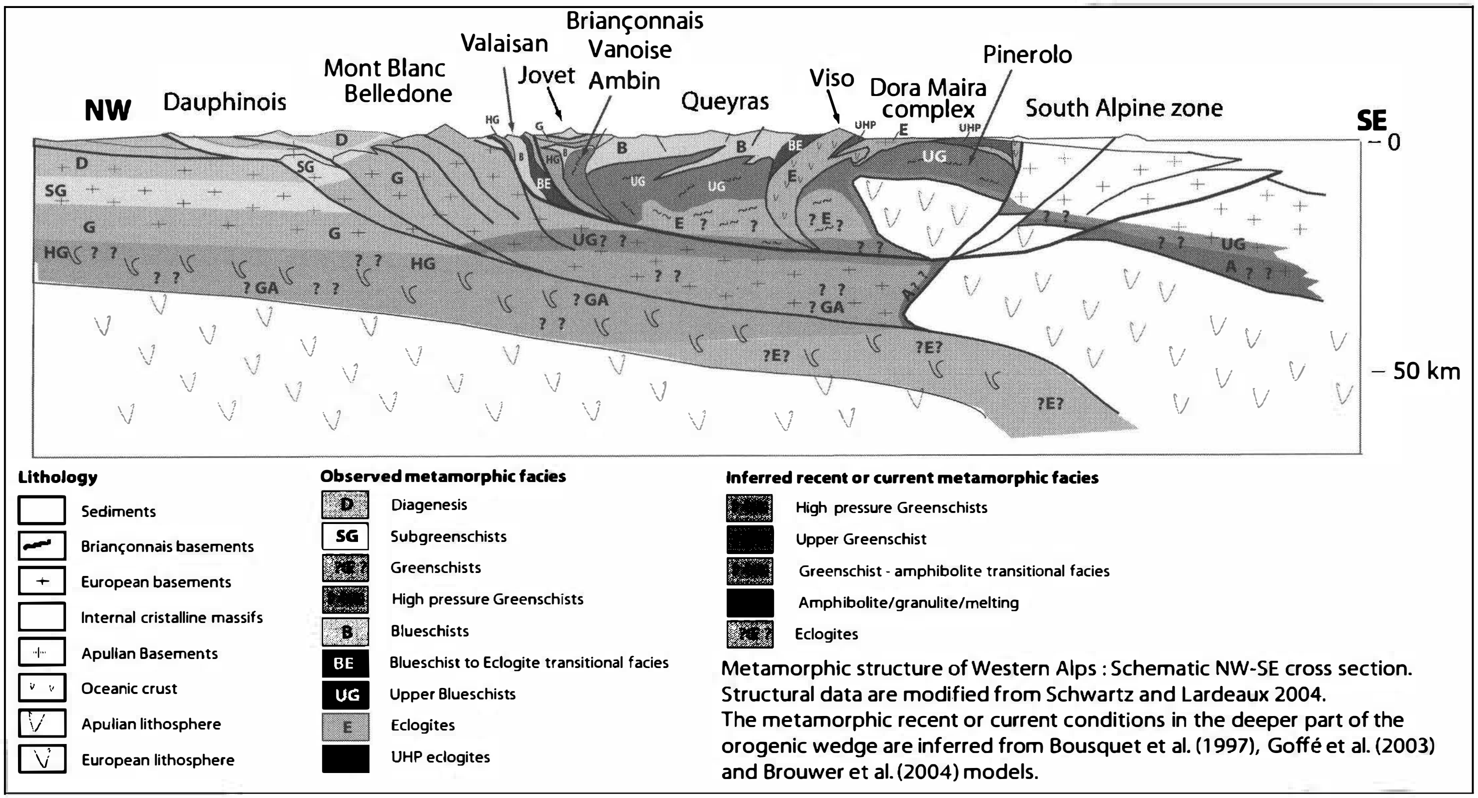


Figure 1

Schematic projected NW-SE cross section of the Western Alps showing the metamorphic structure. The upper part of the cross section is drawn using surface metamorphic data as drawn in the map. The deeper part of the cross section is hypothetically inferred from numerical modelling and data coming from Central Alps, considering this area as a possible further evolution for Western Alps. A moderated thermal imprint is also considered as a possible current deep metamorphic structure resulting from a slab breakoff event as modelled by BROUWER et al. (2004). This metamorphic thermal imprint around the mantel indenter could thus be compared to those observed around the peridotitic bodies of Beni Bousera and Ronda in the Rif and Betic Chain.

3 - The metamorphic facies in the Western Alps

The metamorphic facies used here are mainly based on B. EVANS (1990) metamorphic grid defined for metabasites. In the case of the Western and South-Western Alps, these facies definitions actually cover a large variety of other index minerals depending of the nature of the protoliths, particularly, the metasediments. In the following, the specific index minerals found in the belt are listed and discussed for each metamorphic facies in function of the lithology. In each facies the minerals regarded as defining the metamorphic index mineral assemblages are printed in bold, while additional index minerals, locally present, are added in italic. Localities where a specific mineralogy can be found are indicated in brackets.
For organic matter, only the appearance of graphite is considered to enhance the absence of diamond in the HP conditions. In the other case the organic matter is considered as disordered carbonaceous matter.

- **Sub greenschist facies (200–300°C; P < 4kbar)**
  Mafic system: albite – chlorite – pumpellyite (Chenaillet)
  Volcanoclastic metasediments: **laumontite – prehnite** (Champsaur)
  Pelitic system: **kaolinite – chlorite – illite - interlayered illite-smectite,** *Rectorite (Nappe de Digne)*
  Metabauxites (Prealpes, Devreneuse): **diaspore – kaolinite – berthierite**

- **Lower greenschist facies (300–400°C; P < 4kbar)**
  Mafic system and Volcanoclastic metasediments: **albite – chlorite – epidote – actinolite**
  Na rich metapelites: **albite – chlorite – phengite**
  Al rich metapelites: **pyrophyllite – chlorite – illite-phengite – paragonite** - *cookeite (Ultra-Dauphinois unit, La Grave and la Mure area) – chloritoid (Northern part of Ultra-Dauphinois North of the Maurienne valley) – paragonite*

- **Upper greenschist facies (300–400°C; 4 < P < 8kbar)**
  Mafic system and Volcanoclastic metasediments: **albite – lawsonite – chlorite** – *paragonite – phengites – riebeckite-crossite – pumpellyite – stilpnomelane*
  Pelitic system: **phengite – chlorite** – *chloritoid (Northern Vanoise, Ligurian Alps)*

- **Blueschist facies (300–400°C; 8 < P < 15kbar)**
  Mafic system: **glaucophane – lawsonite – jadeite-quartz** – *pumpellyite*
  Marble and calcschists: **aragonite** - *glaucophane*
  Evaporites (Maurienne Valley near Bramans): **jadeite + quartz – anhydrite** – *selaite – sulfur*
  Pelitic system: **ferro- magnesiocarpholite –phengite** – *chloritoid – pyrophyllite – lawsonite – aragonite – cookeite – paragonite*
  Na rich metapelites: jadeite + quartz – glaucophane – chlorite – *paragonite*
  Al rich metapelites and metabauxites: **ferro- magnesiocarpholite – pyrophyllite – diaspore – chloritoid** – *lawsonite – aragonite – cookeite – paragonite – sudoite (Antoroto metabauxite, Liguria) – gahnite – euclase (Western Vanoise)*

- **Upper Blueschist facies (400–500°C; 10 < P < 15kbar)**
  Mafic system: **glaucophane – epidote** - *garnet or omphacite (+ jadeite)-sphene*
  Granitic System: **phengite – jadeite**- *epidote (Southern Vanoise, Ambin, Acceglio)*
  Pelitic system: **chloritoid – glaucophane – phengite** – *graphite (Southern Vanoise, Ambin massif)*

- **Blueschist to eclogite transitional facies (400–480°C; 15 < P < 20kbar)**
  Mafic system: **glaucophane – epidote** (+ *garnet)* – **omphacite** *(+ jadeite)-sphene*
  Pelitic system: Mg rich **chloritoid – phengite** – *magnesiocarpholite – garnet – graphite*

- **Eclogite facies (500–600°C; 13 < P < 25kbar)**
  Mafic system: **garnet – omphacite – quartz** – *zoisite – phengite- rutile*
  Granitic system: garnet-jadeite-phengite- *zoisite-rutile (Sesia-Lanzo zone)*
  Pelitic system: **chloritoid – kyanite – phengite – garnet** – *glaucophane – paragonite-graphite (Sesia-Lanzo zone)*

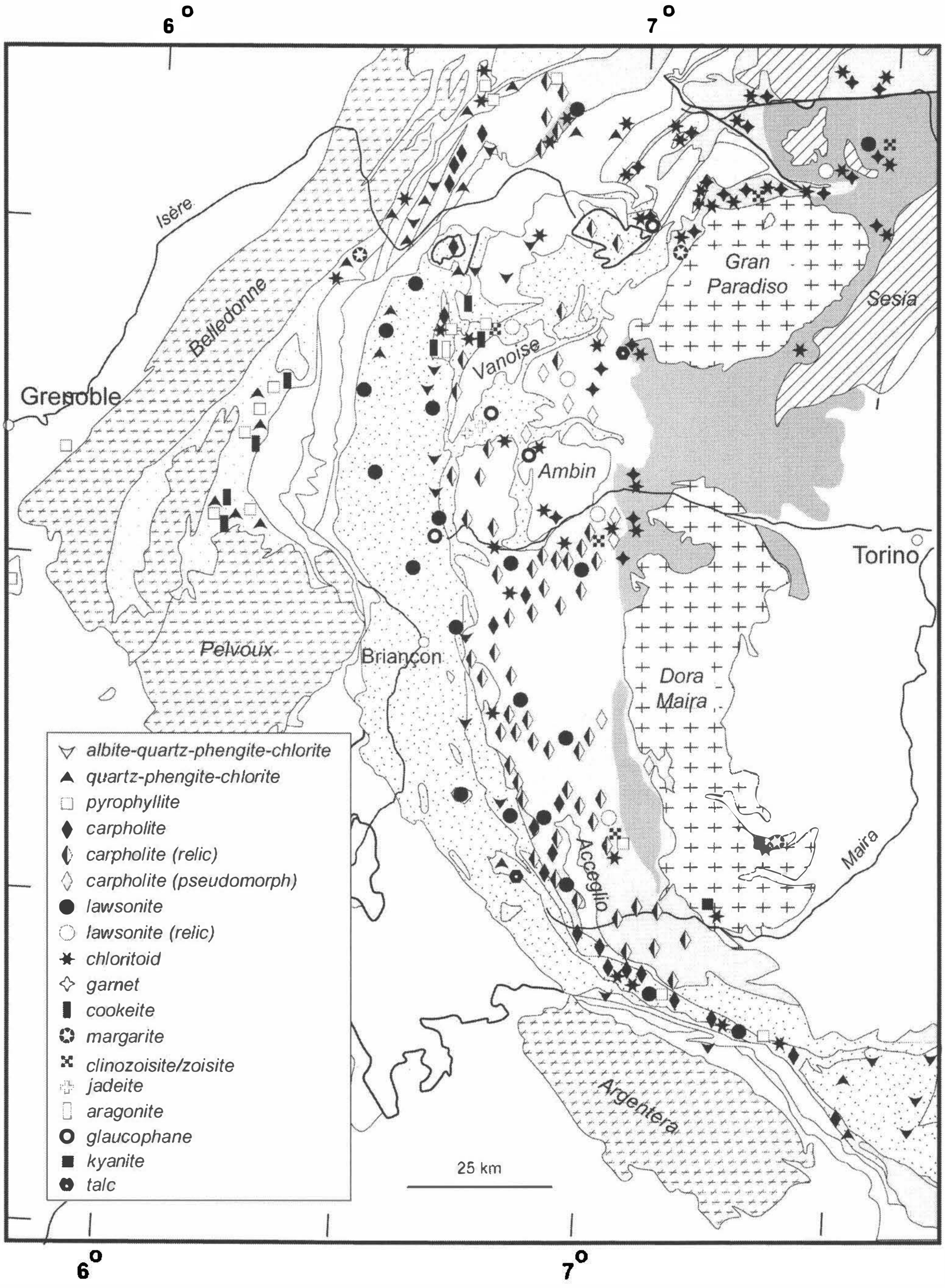
- **Ultra high-pressure facies (600–800°C; 25 < P < 40kbar)**
  Mafic system: **garnet – omphacite – zoisite – coesite** – *kyanite – Mg-chloritoid – talc (Mon Viso)*
  Pelitic system: **Magnesiochloritoid – kyanite – phengite – pyrope – talc – coesite** – *Magnesiostaurolite – ellenbergerite– bearthite – magnesiodumortierite – graphite (Dora Maira massif)*

4 - Diversity of Alpine high-pressure mineralogy: an overview

The diversity of the Alpine metamorphic high-pressure assemblages reflects the contrasted bulk-rock chemistries of the metamorphosed protoliths. Hereafter, we present a review of the metamorphic assemblages recognized in different chemical systems.

a) Metasediments

Compared to the earlier published metamorphic maps FREY et al. (1999), and beside the different choice of the metamorphic representation, the main new data of this present map is the large and continuous expression of the high-pressure and low temperature metamorphic conditions in the metasediments as shown in Figure 2 and 3.
This new data mainly results from the consideration of the ferro- and magnesiocarpholite occurrences in the metapelites. The magnesiocarpholite first discovered in the metabauxites of Western Vanoise (GOFFÉ et al., 1973, GOFFÉ & SALIOT 1977) is now known in all the high-pressure metasedimentary lithologies having initially a low Na content (i.e. bauxite, aluminous pelites, common pelites, sandstones, conglomerates). They occur abundantly in the Briançonnais domain in Western and Southern Vanoise, Cottian and Ligurian Alps, both in the Paleozoic series (Stephanian and Permian schists and metaconglomerates) and in the Mesozoic cover (Triassic series, Dogger metabauxites, Eocene flysch).



a: External Crystalline Basements
b: Briançonnais Basements
c: Internal Crystalline Basements
d: Austroalpines Units
e: High grade metamorphic metasediments (mainly eclogitic)
Oceanic metasediments of theValaisan and Ligurian domain
Continental metasediment of Briançonnais zone
Continental metasediments of Dauphinois and Helvetic domain

Figure 2
Occurrences of metamorphic index mineral observed in Alpine metasediments of the Greenschist and Blueschist metamorphic zones of Western Alps used to draw the metamorphic map.
White: Sediments or very low grade metasediments.

They occurs also widely in blueschists facies metapelites of the Tethys oceanic domain in the Valaisan realm (Versoyen and Brêches de Tarentaise units) and in the Ligurian zone from the more external klippe of Mont Jovet (AGARD, 2001, pers. com.) to the more internal one in the Sestri-Voltaggio-Cravasco unit. Its stability domain in blueschists metamorphic facies and its progressive replacement during the prograde and retrograde metamorphic evolution by chloritoid, chlorite, phengite and generally numerous minerals of the KMASH reduced system can be used to describe and to quantify continuously the metamorphic evolution (GOFFÉ, 1982; CHOPIN 1983; GOFFÉ & CHOPIN 1986; VIDAL et al., 1992; GOFFÉ et al., 1997; JOLIVET et al. 1998; VIDAL & PARRA 2000; PARRA et al., 2002; AGARD et al., 2001; among others). In the Western Alps, ferro- and magnesiocarpholite ranges from 80% of the Fe end member to 85% of the Mg one. In the Briançonnais domain, Fe-Mg-carpholites are commonly associated to pyrophyllite and record pressures between 8 to 12 kbar for temperatures ranging from 330°C to 400°C. In the Schistes Lustrés domain, the Fe-Mg-carpholites are never associated to pyrophyllite and shown equilibrium with phengites through the reaction: Chlorite + muscovite + quartz ⇔ phengite + Fe-Mg-carpholite. The reported maximum pressures for this reaction are around 15-18 kbar for temperatures reaching 480°C (GOFFÉ et al., 1997; AGARD et al. 2001). These conditions are those of the upper blueschists facies reported on the map in the inner part of the Schistes Lustrés domain and the Valaisan, at the external limit of the eclogite domain.

Lawsonite occurrences are also very common in metapelites and calcschists of the Schistes Lustrés units (CARON & SALIOT, 1969; SICARD et al., 1986) and in meta-sandstones of the Briançonnais domain. Lawsonite is often associated to Fe-Mg-carpholite in continental and oceanic metasediments. Its distribution is wider than that of Fe-Mg-carpholite with occurrences in upper greenschist and eclogite facies units, where Fe-Mg carpholite is not stable and was never found. This widest distribution is in accordance with a largest stability field toward both low pressure and high temperature conditions.

Cookeite (lithium chlorite) is also an important metamorphic index mineral in the Briançonnais (Barrhorn, Vanoise, Cottian and Ligurian Alps) and Dauphinois (la Grave, La Mure) domains of the Western Alps. It occurs widely in metapelites, metaconglomerates and metabauxites in association with quartz or diaspore in a large variety of low to high-pressure metamorphic assemblages (GOFFÉ, 1977, 1980, 1984; SARTORI, 1988; JULLIEN & GOFFÉ, 1996). Cookeite records medium temperature conditions (300 to 450°C) of the greenschist to blueschist facies (VIDAL & GOFFÉ, 1991). Cookeite shows a pressure dependence of its polytypism with an increase of structural ordering with pressures from 100 to 1500 Mpa (JULLIEN et al., 1996).

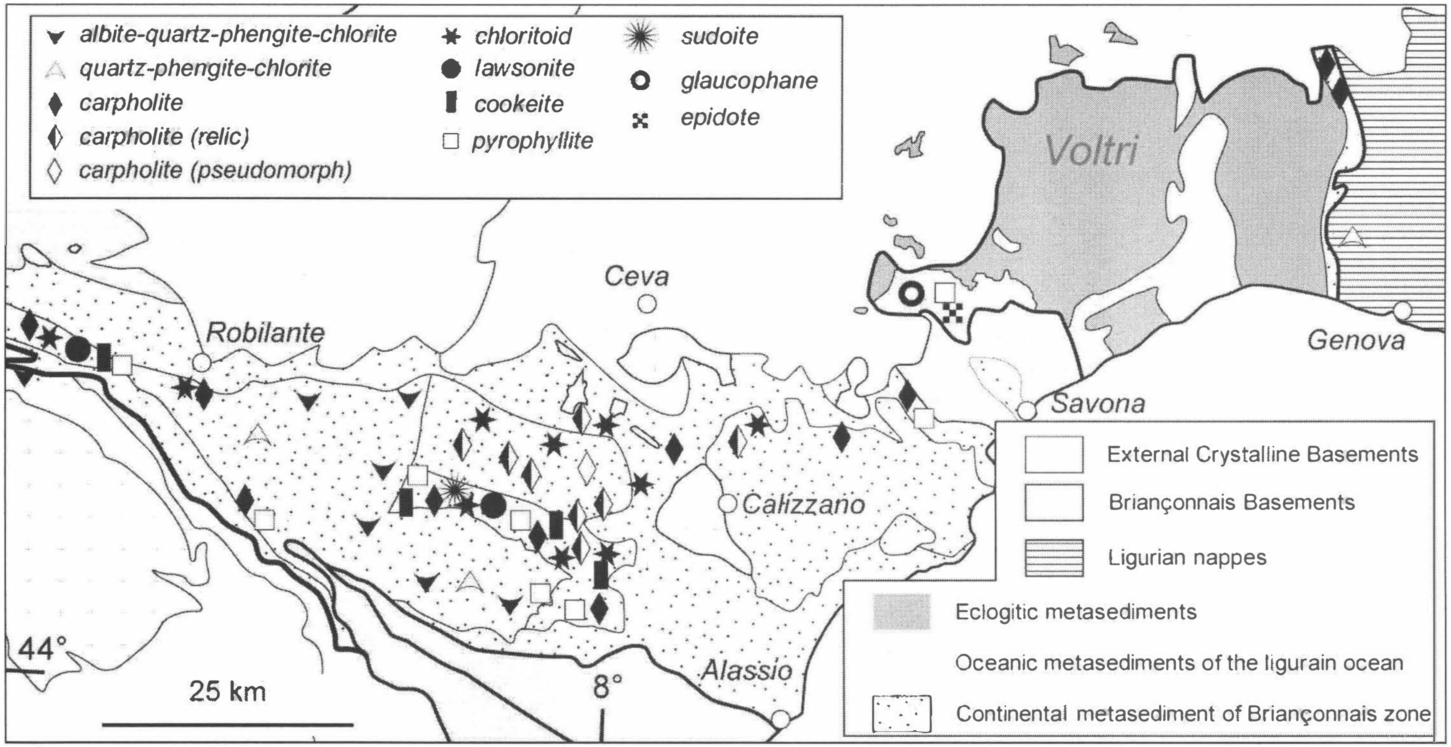


Figure 3

Occurrences of metamorphic index mineral observed in Alpine metasediments of the Greenschist and Blueschist metamorphic zones of Ligurian Alps used to draw the metamorphic map. The structural frame is from the general map.

Very high metamorphic conditions lead the metapelitic system to react continuously to give appearance to kyanite which is associated to a specific mineralogy showing a linear increase of Mg content with the metamorphic grade. This results in pure Mg-endmembers of FMASH system minerals in the coesite stability field such as: magnesiochloritoid, magnesiostaurolite, pyrope, talc, clinochlore in association with unique very high pressure minerals like ellenbergerite, magnesiodumortierite or bearthite (CHOPIN and CHOPIN et al., 1981-1995, SIMON et al., 1997).

Under quartz-eclogite facies conditions, metapelites have been described and analysed in details since their discovery in the Sesia-Lanzo zone (DAL PIAZ et al, 1972; COMPAGNONI et al., 1977; LARDEAUX et al., 1982; VUICHARD & BALLÈVRE, 1988), where the association of quartz, phengite, jadeite, chloritoid, garnet and glaucophane characterizes the so-called "eclogitic micaschists". Similar well preserved eclogitic metapelites occur in other Austro-Alpine units of the Western Alps for example the Monte Emilius massif (DAL PIAZ et al., 1983).

The organic carbonaceous matter of the metasediments is also an interesting way to follow the metamorphic evolution. The organic carbonaceous matter is particularly abundant in the Western Alps either as coal in the Briançonnais domain or as diffuse marine organic matter in the Schistes Lustrés series. With increasing metamorphic grade the organic matter evolvs continuously from disoriented structures (turbostratic) in the sub-greenschist facies to perfectly organized graphite in UHP facies in the Dora Maira massif through carbons having peculiar onion like shaped structures in the blueschist facies (BEYSSAC et al., 2002). This evolution can be linked to the temperature evolution without evidences of a pressure effect (BEYSSAC et al., 2002). Graphite appears in high temperature and high-pressure blueschist facies. Diamond was never found, neither characteristic carbonaceous structures resulting of its retromorphosis (BEYSSAC & CHOPIN, 2003). Anomalous well preserved organic matter (C_n gas, liquid hydrocarbons, low evolved solid carbonaceous matter) are reported in the blueschist facies of the Western Vanoise (GOFFÉ, 1982, GOFFÉ & VILLEY, 1984).

b) Mafic rocks

Mafic rocks from the Western Alps represent ophiolite suites mainly formed during the opening of the Piemont-Ligurian oceanic basin durin Jurassic times (LOMBARDO et al., 1978; POGNANTE, 1980; LOMBARDO & POGNANTE, 1982). However, a limited number of mafic rocks derive from metamorphosed continental crust as for example meta-amphibolites and meta-granulites from the Sesia-Lanzo zone (LARDEAUX & SPALLA, 1991).

Mineralogical and geochemical studies have demonstrated that the Western Alps ophiolites derive from partial melting of rather homogeneous peridotites which generated melts similar to normal – MORB. Consequently Alpine metabasalts represent differentiated (Fe-Ti rich) tholeiitic liquids. On the other hand, metagabbros display a wide spectrum of compositions ranging from Cr-Mg rich gabbros to Fe-Ti gabbros. Therefore, the so-called mafic metamorphic rocks in the Western Alps derive from the variuos protoliths following a tholeiitic differentiation trend:

Mg (± Cr) rich gabbros: olivine-bearing cumulates,
Intermediate gabbros: gabbro-norites,
Fe-Ti rich gabbros: ilmenite and magnetite-bearing gabbros,
Fe-Ti rich basalts

Moreover, some of these lithologies have been subjected to ocean-floor hydrothermal activity leading to the development of rodingitic alterations. When affected by high-pressure Alpine metamorphism, these rocks correspond to metarodingites with peculiar mineralogical associations (BEARTH, 1967; DAL PIAZ, 1967).
In our metamorphic map, we select Fe-Ti rich metabasalts and metagabbros for the definition of the metamorphic facies because, in comparison with other gabbro compositions, the ophiolitic Fe-Ti rocks show better developed high- pressure and low-temperature metamorphic assemblages. Metagabbros, in many cases, show incomplete metamorphic recristallization allowing to study reaction mechanisms at the boundaries between the magmatic mineral relics.

At quartz-bearing eclogite-facies conditions, the following mineralogical associations have been recognized (LOMBARDO et al, 1978; DAL PIAZ & ERNST, 1978; LARDEAUX et al., 1986, 1987; POGNANTE & KIENAST, 1987).

Mg (± Cr) rich metagabbros: omphacite (± smaragdite), pale blue/colourless glaucophane, zoisite, ± chlorite, ± Mg-chloritoid, ± talc,± kyanite, ± scarce garnet, ± fuchsite
Intermediate metagabbros: omphacite , garnet, zoisite, glaucophane, ± jadeite, ± talc, ± paragonite
Fe-Ti rich metagabbros and metabasalts: omphacite (± jadeite), garnet, zoisite, rutile, glaucophane, ± paragonite, ± phengite, ± clinozoisite, ± Fe-talc
Metarodingites: diopside and / or «omphacitic clinopyroxene», grandite and / or grossular rich garnet, epidote, chlorite, ± idocrase, ± amphibole, ± Ti-clinohumite

Under blueschist-facies conditions, the following associations have been described:

Mg (± Cr) rich metagabbros: Amphibole, chlorite, clinozoisite, ± white micas
Intermediate metagabbros: Na-amphibole, chlorite, ± clinozoisite, ± sphene, ± lawsonite
Fe-Ti rich metagabbros and metabasalts: Acmite-rich clinopyroxene, «omphacitic» clinopyroxene, glaucophane, epidote (or lawsonite), sphene, ± garnet, ± white micas

In Fe-Ti matagabbros, at P-T blueschist facies conditions, the chemical evolution of the clinopyroxenes is controlled by the existence of non-omphacitic unmixing domains for temperatures lower than 350°C (CARPENTER, 1980). Fe-Ti metagabbros show different chemical evolution of their initial magmatic clinopyroxene (augitic-cpx). Indeed, under low-temperature blueschist facies conditions (i.e. lawsonite-glaucophane conditions), the increase of the P-T conditions during Alpine metamorphism is recorded by an increase of the Fe-content in clinopyroxene from the core to the rim of the initial magmatic clinopyroxene, with apparition of acmite-rich clinopyroxene on the crystal rims (POGNANTE & KIENAST, 1987). Whereas under high-temperature blueschist (i.e. zoisite-glaucophane conditions), the increase of the P-T conditions during Alpine metamorphism is characterized by an increase of the Na component in clinopyroxene leading to the crystallisation of omphacite (SCHWARTZ, 2001).

Spectacular metamorphic transformations can be observed in mafic rocks of continental origin. In eclogitized amphibolites and granulites, high-temperature calcic amphiboles are progressively replaced by calco-sodic (barroisite) and sodic amphiboles (glaucophane), sometimes in association with phengites. Associations of zoisite, garnet and omphacite are developed at the expense of plagioclase or at the plagioclase/amphibole, plagioclase/ilmenite or plagioclase/pyroxene boundaries, while coronas of rutile are frequently developed around ilmenite grains.

c) Meta-granitoids

In the Western Alps the following protoliths have been recognized for the meta-granitoids:

Biotite- bearing granites and granodiorites,
Two-micas granites,
Fe-rich syenites,
Trondhjemites, plagiogranites and quartz-keratophyres in ophiolites.

It should be underlined that eclogitized metagranites from the Sesia-Lanzo zone have been regarded as the first indication for the subduction of the continental crust (DAL PIAZ et al., 1972; COMPAGNONI & MAFFEO, 1976; COMPAGNONI et al., 1977; LARDEAUX et al., 1982; OBERHÄNSLI et al., 1982).

Under quartz-eclogite facies conditions, in mica-rich granites and granodiorites, the igneous mineralogy is replaced by an high-pressure metamorphic association composed of: jadeite, phengite, garnet, zoisite, rutile and quartz. K-feldspar is generally recristallised but remains stable sometimes with intergrowths of white micas and quartz. An association of jadeite and zoisite replaces plagioclase, while, close to the biotites/plagioclases boundaries, Ca-rich garnet develops as thin coronas. Biotites are replaced by coronitic garnets and an association of phengite, quartz and rutile. Magmatic muscovites are replaced by celadonites-rich white micas, while quartz recristallised (sometimes in coesite) and zircons, apatite and tourmalines remain as recital phases.

In Fe-rich syenites (LARDEAUX et al., 1983), the metamorphic high-pressure mineralogy is composed by ferro-omphacites, garnets and epidotes.

In leucocratic rocks from Alpine ophiolites (i.e. trondhjemites, quartz-keratophyres or plagiogranites), the Alpine eclogite facies metamorphism leads the development of: jadeite, quartz, phengite, ± garnet, ± epidote and rutile (LOMBARDO et al., 1978; POGNANTE et al., 1982).

Meta-granitoids reworked under blueschist facies conditions have been described in Vanoise, Ambin and Acceglio massifs (GAY, 1973; SALIOT, 1978; GANNE et al., 2003; ROLLAND et al., 2000; SCHWARTZ et al., 2000). In the Acceglio massif the metamorphic conditions reach the transition between high-temperature blueschist and eclogite facies conditions. The observed metamorphic assemblages consist of an association of quartz, jadeite, phengite, lawsonite or epidote, ± almandine-rich garnet. Secondary magmatic minerals like zircons, apatite and tourmaline are frequently well preserved.

5 - Conclusions

The metamorphic structure of the western part of the Alpine belt shows probably the best preserved example of the "Alpine-type" metamorphism with a continuous evolution of high pressure conditions from very low temperature conditions to the highest ones. These conditions can be observed in all lithologies with a near theoretical coherence between them.

As shown in the synthetic cross section through the Western Alps (Fig.1), these high-pressure and low-temperature conditions can be considered as relicts of the early (pre Oligocene) evolution of the belt related to the subduction processes. Three main geodynamic consequences can be emphasised after our metamorphic analysis:

Even in a mature collisional belt like the Western Alps, the memory of subduction processes should be well preserved in a fossil accretionnary wedge like the western internal Alps.

Both oceanic and continental crustal slices should be involved in the subduction zone during plate convergence. In Western Alps, numerous examples of subducted continental crust have been exhumed and are now preserved in Austro-Alpine (i.e. Sesia-Lanzo, Mt. Emilius klippe, etc.) and Penninic units (i.e. Internal Crystalline Massifs, Dora-Maira, Gran-Paradiso, Monte Rosa, etc.).

The huge mass of weathered sediments issued from the erosion of the Hercynian belt and reworked during the Thethys opening along its passive margins, led to a peculiar metamorphic belt constituted by a large metasedimentary orogenic wedge characterized by prevalent high pressure-low temperature conditions (GOFFÉ et al. 2003). This could be considered as the definition of the so-called Alpine type metamorphism sensus stricto characterized by a high-pressure – low-temperature regime of 10°C/km or less. These metamorphic conditions contrast with those prevailing early in the Eastern Alps and lately in Central Alps where the pressure-temperature ratio is highest even at high pressure (see the map) and where mainly continental crust is involved in the orogenic process.

Now, the present-day ongoing continental collision process involves the European crust and the thermal regime is changing. Alpine metamorphism evolves from the early high-pressure and low-temperature conditions to present-day high-temperature and medium-pressure metamorphic conditions. These conditions, clearly expressed in the Central Alps, can be already observed in the external part of the Western Alps around the external crystalline massifs and probably prevail at depth in the orogenic root (Fig. 1).

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EXPLANATORY NOTES TO THE MAP: METAMORPHIC STRUCTURE OF THE ALPS TRANSITION FROM THE WESTERN TO THE CENTRAL ALPS

by

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The northern-western Alps, located between two major tectonic structures, the Simplon and the Aosta-Ranzolla faults, represent a "transition" zone where all paleogeographic domains involved within the alpine orogenic wedge are present and clearly distinguishable on a map (e.g. BIGI et al., 1990; SCHMID et al., 2004). The structural style and metamorphic record in the area linking the West and South-West Lepontine to the Western Alps has particular characteristics, which warrant this separate chapter. This concerns the Lepontine zone from just East of Valle d'Ossola to the western limit set by the continental Bernhard nappe system in the North-West, the ocean-derived Piedmont-Ligurian zone and its prolongation to the west (Préalps), as well continental units issued either from the Adriatic continent domain (Sesia and Dent-Blanche massifs) or from the European margin (Mt Blanc massif).
All units will be described after that from east to west following Figure 1, while structural relationship between different units is described in details in SCHMID et al. (2004).

Sesia zone

The Sesia Zone (SZ) of the western Austroalpine is a huge portion of Alpine continental crust widely recording alpine eclogite-facies assemblages. For the very first time it was possible to demonstrate that even granites were brought outside the stability field of plagioclase and recrystallized under eclogite facies conditions (DAL PIAZ et al., 1972; COMPAGNONI & MAFFEO, 1976; COMPAGNONI et al., 1977; LARDEAUX et al., 1982; OBERHÄNSLI et al., 1982).

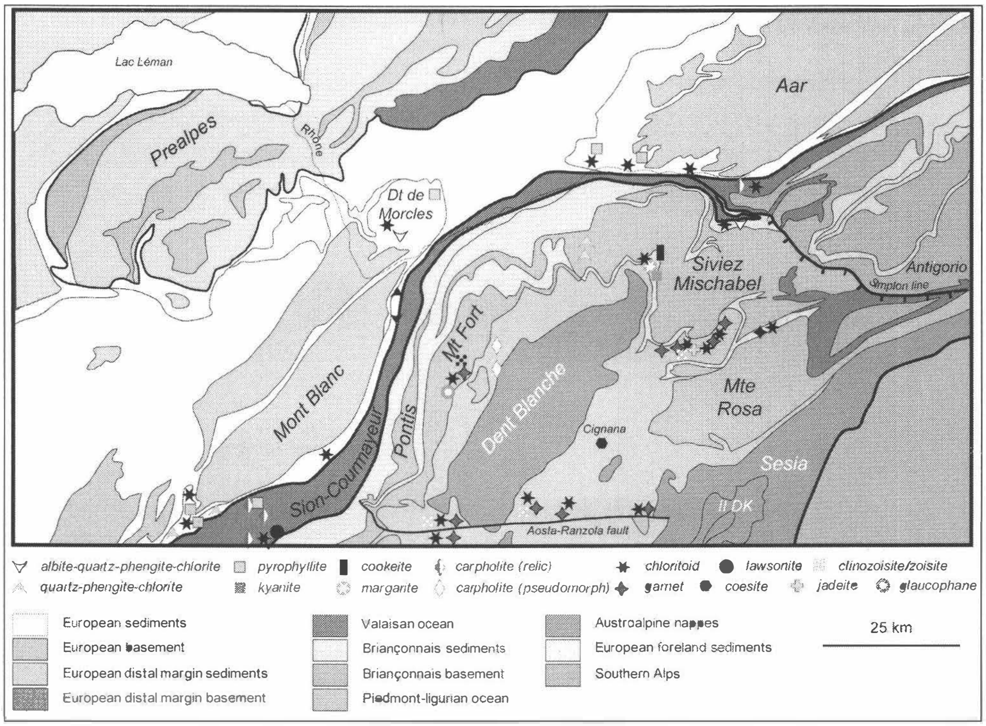

Figure 1

Structural map of the "transition" area between the Simplon line and the Aosta-Ranzola fault (after BIGI et al., 1990; SCHMID et al., 2004) displaying occurrences of metamorphic index mineral indicating greenschist, blueschist and eclogites metamorphic conditions observed in Mesozoic Alpine metasediments.

The Sesia Lanzo zone consists of an upper and a lower unit: the lower unit comprises the Gneiss Minuti Complex (GMC) and the Eclogitic Micaschists Complex (EMC), whereas the upper unit is constituted by the II Dioritic-Kinzigitic Zone (IIDK and Vasaro units; e.g. COMPAGNONI et al., 1977; POGNANTE et al., 1987). The upper unit is characterised by high-pressure blueschist mineral assemblages and its contact with the lower unit is marked by mylonitic belts, developed under eclogite or blueschist facies conditions (LARDEAUX et al., 1982; POGNANTE et al., 1987) and later overprinted by greenschist facies mylonites (RIDLEY, 1989; STÜNITZ, 1989). In the central and southern part of the lower unit, the alpine evolution is characterised by a LT eclogite imprint, following by a blueschist re-equilibration during the decompression (e.g. CASTELLI, 1991; POGNANTE, 1991 and references therein), and then by a low-pressure greenschist facies overprint (OBERHÄNSLI et al., 1985). Gneiss Minuti Complex and Eclogitic Micaschists Complex, both pervasively eclogitized, strongly differ in the volume percentage of greenschist retrogression. The Gneiss Minuti Complex, is widely re-equilibrated under greenschist facies conditions. This greenschist imprint is generally associated to mylonitic textures (STUENITZ, 1989; SPALLA et al., 1991). On the other hand, in the Eclogitic Micaschists Complex, which constitutes the innermost part of the Sesia Zone, the greenschist facies overprint is confined to discrete shear zones, more pervasively developed towards its inner boundary with the Southern Alps.

The Alpine structures are crosscuting by calc-alkaline and ultrapotassic dykes during Oligocene (DAL PIAZ et al., 1972, 1979). In the southernmost part of the massif, some thrust sheets, the metamorphic complex of Rocca Canavese thrust sheets, display mineral assemblages indicating blueschist facies conditions (POGNANTE, 1989a; 1989b). These thin tectonic slices are separated from each other by alpine blueschist mylonitic horizons. These differences in mineralogical occurrences could be interpreted either as an effect of the chemical composition of the rocks (RUBIE, 1986; RIDLEY, 1986) or by different metamorphic evolution. In this latter case, the coupling of EMC, GMC and RCT units is interpreted to have occurred in blueschist facies conditions, synchronous with the early exhumation stages of the Eclogitic Micaschists Complex (POGNANTE, 1989b). In the northern part of the Sesia zone SLZ, the lower unit display mineral assemblages indicating upper blueschist facies conditions similar to those of the upper (IIDK) unit.

The very low T/P ratio, characterising the SLZ Alpine metamorphic history, favours preservation of pre-Alpine relic assemblages in spite of several a strong greenschist overprint. This ancient granulite to amphibolite evolution could be interpreted as consequent to a lithospheric extension-related uplift of the pre-Alpine lower crust, during Permo-Triassic times (DAL PIAZ, 1993; LARDEAUX & SPALLA, 1991; REBAY & SPALLA, 2001).

Piedmont-Ligurian unit

The Piedmont-Ligurian zone in the north of the Western Alps is classically divided into two units, the Tsaté nappe (or Combin zone) and the Zermatt-Saas nappe (e.g SARTORI & THÉLIN, 1987; DAL PIAZ, 1999 and references therein), separated by a major extensional fault (BALLÈVRE & MERLE, 1993; REDDY et al., 2003). The distinction between both units was based both on lithostratigraphic (BEARTH, 1962; MARTHALER, 1984; MARTHALER & STAMPFLI, 1989) and on metamorphic differences (DAL PIAZ, 1965; KIENAST, 1973; CABY et al., 1978).
The lowermost unit, the Zermatt-Saas nappe, is composed mainly of mafic and ultramafic ophiolites, displaying an oceanic affinity. Since the famous BEARTH'S work, this nappe is well known for its high-pressure mineral assemblages (BEARTH, 1967; ERNST & DAL PIAZ, 1978; CHINNER & DIXON, 1973). The discovery of coesite inclusions within garnet in some Mn-bearing metasediments in Lago di Cignana suggests that some piece of the Piedmont-Ligurian were deeply subducted up to 28 kbar at 600°C (REINECKE, 1991). The most eclogites of the Zermatt-Saas nappe display high-pressure mineral assemblages formed by omphacite-garnet-chloritoid-talc-zoisite or omphacite-garnet-kyanite-clinozoisite ± talc (OBERHÄNSLI, 1980; BARNICOAT & FRY, 1986; GANGUIN, 1988). The eclogites are strongly retrogressed into epidote amphibolites ± garnet toward the contact with the uppermost unit in the West.

The uppermost unit, the Tsaté nappe, is an ophiolitic unit dominated by carbonate and terrigeneous calcschists, alternating with tholeiitic metabasalts. The lack of eclogites and relics of sodic amphiboles in metabasites (DAL PIAZ & ERNST, 1978; AYRTON et al., 1982; SPERLICH, 1988) as well in Mn-rich quartzitic schists associated with Mn-rich garnets (DAL PIAZ, 1979b; CABY, 1981) have been led to consider the Tsaté nappe to have overall the same metamorphic evolution, both western and eastern of the Dent-Blanche. However the ground of metasediments shows a metamorphic gradient from west to east (Fig. 1).

Calcschists and other terrigeneous sediments display pseudomorphs after carpholite (PFEIFFER et al., 1991) in the west and relics of garnet, Mg-rich chloritoid and phengite assemblages in strongly retrogressed albite-rich metapelites in the east at the contact with eclogites of the Zermatt-Saas nappe.
At the base of the Tsaté nappe occur discontinuous exotic sheets of continental origin (Cime Bianche and Frilihorn units) displaying jadeite-quartz-phengite mineral assemblages (SCHAUB, pers. com.).

The western end of the Lepontine dome and the Monte Rosa

The western culmination of the Lepontine Alps (i.e. the Toce dome) emparts a westerly axial plunge to the Pennine nappe stack. This results in successively higher thrust sheets being visible at today's erosional level, from the lowest Penninic gneiss units (e.g. Antigorio nappe) up to the Austroalpine Dent Blanche nappe appearing at the top, some 50 km further west. The nappe system is polydeformed and cut by the late orogenic (D4) Simplon fault, running to the NW from Valle d'Ossola to Simplon Pass. Tectonic unroofing by this major ductile/brittle normal fault (MANCKTELOW, 1985) brought the high grade Lepontine belt into a position opposite the greenschist facies Grand St-Bernard nappe system. The NW-part of the Simplon line marks the western limit of the Central Alpine amphibolite facies. In the Simplon area this Barrovian overprint has been dated at ~30 Ma (garnet growth in metaclastics, VANCE & O'NIONS, 1992). By contrast, in the area W and SW of Domodossola the Barrovian amphibolite facies/greenschist facies boundary crosscuts all major tectonic boundaries, and the medium pressure overprint is the sequel of an earlier (Eocene) HP-history. Decompression stages dated between 38 and 32 Ma in the western Monte Rosa nappe, but as young as 26 Ma in its eastern section (ENGI et al., 2001b), can be linked with the evolution in the Moncucco-Camughera unit, where KELLER (2004) showed the Barrovian reequilibration to be associated with D3 backthrusting (top-WSW) and dextral shearing at amphibolite facies conditions. These are responsible for the sillimanite and staurolite zone boundaries shown in (Fig. 2); as in the eastern TAC units (NAGEL et al., 2002; ENGI et al., 2004) these Al-phases were formed at the expense of paragonite and phengite during decompression (at $P \sim 1.1$-0.8 MPa), but with no evidence of a heating spike (KELLER, 2004). In the upper parts of the Monte Rosa nappe and westerly adjacent units, the decompressional Barrovian overprint reached only greenschist facies, as shown already by BEARTH (1958) who mapped the albite/oligoclase isograd (Fig. 2).

The geometry of the metamorphic zone boundaries in the westernmost Lepontine and southerly adjacent nappes is remarkable, as it reflects (a) the rapid exhumation of the Pennine nappe stack of the Central Alps, and (b) the strong dextral transpression at their southern contacts. This lead to a far more rapid thermal quench in the eastern part of the Central Alps (in ENGI et al., 2004), with closely spaced isotherms as compared to the western part, where they are more widely spaced. The successive transfer of heat from the Central Alpine block is also reflected in the succession of isograds extending to the south of the Centovalli line, a ductile-brittle fault running from Locarno to Valle d'Ossola (Fig. 1), which evidently served as a major truncation surface in the late-Alpine exhumation history of the Central Alps.

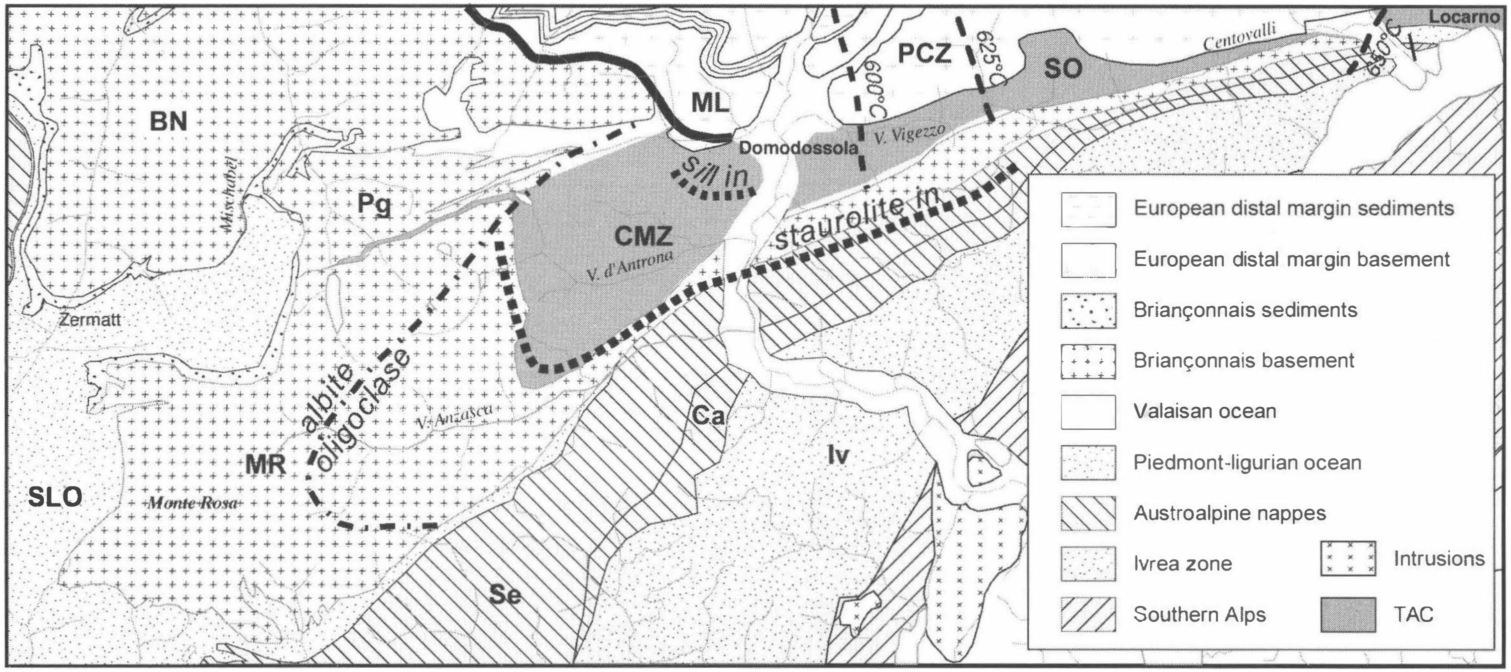

Fig. 2

Metamorphic elements in the transition zone from the Central Alps to the Western Alps, updated from ENGI et al. (2001b) using data from KELLER (2004).
Iv: Ivrea Zone, ML: Monte Leone nappe, MR: Monte Rosa nappe, Se: Sesia zone.

The Monte Rosa nappe and in its footwall neighbors (Camughera-Moncucco and Antrona unit) are tentatively considered to be part of the tectonic accretion channel (TAC, ENGI et al., 2001a). These TAC units reveal evidence of an ealier collisional HP phase which reached eclogite facies during D_1/D_2 decompressional deformation, with top to N or NW thrusting (KELLER, 2004). HP metamorphism has also been extensively documented from units further to the SW and W. Recent geochronological results, however, challenge the earlier views of a common eclogite stage for these two groups (e.g discussion in HANDY et al., 2004). It appears now that the classic "Eoalpine" stage (DAL PIAZ et al., 1972; HUNZIKER, 1974), which is Late Cretaceous according to more recent data (reviewd by DAL PIAZ, 1999) is restricted to units such as the Sesia-Lanzo zone (as well as units of the Western Alps s.s.), whereas the the Saas-Zermatt zone, Monte Rosa nappe, and underlying units reached eclogite facies during the Eocene (CHOPIN & MONIÉ, 1984 and summary in DAL PIAZ, 1999), with maximum pressures of 1.4-1.6 GPa at 500-550°C (BORGHI et al., 1996; ENGI et al., 2001b; KELLER, 2004). The last pre-Tertiary metamorphic imprint in the Monte Rosa nappe is not Cretaceous but Permian and yielded widespread low-P assemblages (BEARTH, 1952, PAWLIG & BAUMGARTNER, 2001).

Dent Blanche

The alpine metamorphic events in the Dent Blanche rocks are polyphase. The last major phase of metamorphism affecting all rocks of this unit produced mineral assemblages of the lower to upper greenschist facies. This greenschist facies event was preceded by subduction related high-pressure metamorphism. The rocks of the Dent Blanche nappe have been affected in various degrees by this event and the preservation of high-pressure indications is variable. Contrarily to the underlying eclogite facies rocks of the Zermatt-Saas Fee unit (BEARTH 1959, 1967), the Dent Blanche rocks only experienced epidote-blueschist facies or transitional alkali-amphibole greenschist facies conditions (BALLÈVRE & MERLE, 1993; CORTIANA et al., 1998). Sodic amphiboles were found in mylonites along the contacts of Permian Gabbros (STRØN, 1990) and in the northernmost part of the nappe (AYRTON et al., 1982). The gneisses of the Arolla series also contain relics of the Eo-alpine event. Thermobarometry with phengite+Kfsp+biotite+chlorite yields P-T conditions of 0.10 to 0.12 GPa and 350-400°C (OBERHÄNSLI & BUCHER, 1987; BUCHER et al., 2004). The rocks of the Valpelline series contain chloritoid and kyanite replacing sillimanite as indicators of a high-pressure phase (KIENAST & NICOT, 1971; DE LEO et al., 1987; CANEPA et al., 1990; PENNACCHIONI & GUERMANI, 1993). An early Alpine assemblage of glaucophane-crossite and aegirine-augite coexisting with phengite yielded an age of 75 Ma in the Pillonet klippe (CORTIANA et al. 1998).

The Briançonnais domain

The Briançonnais microcontinent in this part of the Alps, classically called Grand St-Bernard nappe system (LUGEON & ARGAND, 1905), consists of several units (see details in ESCHER, 1988; GOUFFON, 1993) that display different metamorphic evolution (THÉLIN et al., 1994). The major part, of the called Grand St-Bernard nappe system, formed by the Houillère zone and the Siviez-Mischabel unit, displays a metamorphic evolution within greenschist facies conditions.

The Siviez-Mischabel unit is characterized by an augen-schist horizon with albite mega-porphyroblasts that extends for hundred kilometres along the contact with the basement. Texture and mineralogy vary little in this horizon and indicate a synkinematic crystallization of albite porphyroblasts (SARTORI & THÉLIN, 1987).
In two units, one in the north (the Barrhorn series), one in the south (the Pontis unit), high-pressure greenschist mineralogy has been described. The Barrhorn series, located on the top of the Siviez-Mischabel unit, contains pockets of. The rock-forming minerals of the metabaxites are phengite, Zn-staurolite, kyanite, margarite, chloritoid, diaspore, paragonite ± cookeite (SARTORI, 1990; CHOPIN et al., 2003). Southward in the Pontis unit, pinched between the Houillère zone and the Siviez-Mischabel unit, micaschists contain neocrystallization of chloritoid ± kyanite (OULIANOFF & TRÜMPY, 1958) parallel to the main foliation (GOUFFON & BURRI, 1997). Paradoxically this is the uppermost unit of the Grand St-Bernard nappe system, the Mont Fort unit that display the deepest evolution into high-pressure metamorphic conditions. The Alpine metamorphic evolution is characterized by extensive development of mineral assemblage of epidote-blueschist facies conditions: chloritoid, glaucophane, epidote, garnet, phengite (SCHAER, 1959; BEARTH, 1963).

The "external" units: Valaisan - Mt Blanc - Préalps

Pinched between two continental domains (the Briançonnais microcontinent and the European margin), metasediments of the Sion-Courmayeur zone represent a second oceanic domain, the Valaisan ocean, situated north to the Piedmont-Ligurian (FRISCH, 1979; STAMPFLI, 1993). Metamorphism of this area is characterized by high-pressure conditions (blueschist to eclogites, BOUSQUET et al., 2002; GOFFÉ et al., 2004).
The Mont Blanc massif is one of several Variscan "external crystalline massifs" of the European margin within western and central Alps. It is made of paragneisses, orthogneisses, migmatites and granites (BONIN et al., 1993). During the Tertiary, the Mont Blanc massif was affected by the Alpine orogeny and developed a non pervasive greenschist facies metamorphic assemblage that consists, in granites, of quartz, albite, muscovite, biotite, chlorite, epidote and stilpnomelane (VON RAUMER, 1974; BORGHI et al., 1987). The Mont Blanc Massif is also well known for its hydrothermal veins mainly filled by chlorite, quartz, muscovite, adularia and calcite (POTY et al., 1974). These veins have been dated at 13-18 Ma in the granite using K/Ar and Rb/Sr techniques on adularia and muscovite (LEUTWEIN et al., 1970) and are contemporaneous with shear zones containing biotite-muscovite-chlorite-epidote-quartz-albite assemblages.
The Préalps consist of cover nappes of Triassic to Eocene formations, derived from the Valais, Briançonnais and Piedmont-Ligurian domains. These nappes escaped of their original setting before that these later undergone in subduction. Thus the Préalps suffered only low metamorphic conditions. Occurrences of diaspore, pyrophyllite, paragonite, phengites and corrensite in the Préalps Médianes (JABOYEDOFF & THÉLIN, 1996, and references therein) and of prehnite, pumpellyite, epidote, actinolite, sodic amphibole, stilpnomelane in gabbro and diabase of the Gêts nappes are the main indicator of the low metamorphic conditions (BERTRAND, 1970; BILL et al., 2001). This main metamorphic event affected the Préalps during their Penninic origin, and the process responsible for the metamorphism was progressive burial by thrust stacking, probably during late Eocene (JABOYEDOFF & THÉLIN, 1996).

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EXPLANATORY NOTES TO THE MAP: METAMORPHIC STRUCTURE OF THE ALPS CENTRAL ALPS

by

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The area of the Central Alps (Fig. 1) is delimited by the Subalpine Swiss Molasse to the north, the Austroalpine nappes in the Grisons and the Bergell in the east, and the Insubric Line to the south. The western limit is geologically less evident and is somewhat arbitrarily set in the Simplon area. Within the core portion of the Alpine orogen, some 72% of the (pre-Quarternary) units exposed have witnessed at least one pre-Alpine orogeny. Evidence of polymetamorphism is thus widespread in the basement; relics from the Variscan (Hercynian), Caledonian, and even Precambrian orogenies have been recognized. The intensity of the Alpine overprint is quite variable, and this had plagued early efforts of documenting regional metamorphic patterns (NIGGLI, 1974). Over the past thirty years it has become possible, despite the poly-orogenic metamorphic record, to decipher the Alpine cycle in considerable detail, by combining tectonic and seismic studies with petrology and geochronology.
The Central Alps comprise units attibuted to four paleogeographic domains, from N to S:

Domain	*Original setting*
Helvetic shelf	Distal continental margin of the European craton
North-Pennine (= Valais)	Small oceanic basin (opening: Early Cretaceous)
Middle Penninic (= Briançonnais)	Microcontinental platform
South Pennine (= Piemont-Liguria)	Oceanic basin (opening: Middle Jurassic)

The Austroalpine orogenic lid has been entirely removed, by erosion and tectonic unroofing, in the area of the Central Alps. Whereas their external parts (Helvetic nappes and Penninic Prealps; Fig. 1) are almost entirely composed of post-Variscan shelf sediments, the imbricate thrust sheets in the Lepontine area are dominated by pre-Triassic crystalline cores. These basement units (of the European and Briançonnais domains) comprise largely supracrustal rock types, with abundant granitoid gneiss and clastic schist, subordinate amphibolite, and only minor other rock types. Relics of pre-Alpine orogenic reworking are more abundant in the External Massifs and in the northern parts of the Lepontine area, where the Alpine overprint is modest, but even in units which during the mid-Tertiary reached upper amphibolite facies, traces of a polycyclic history are not uncommon.

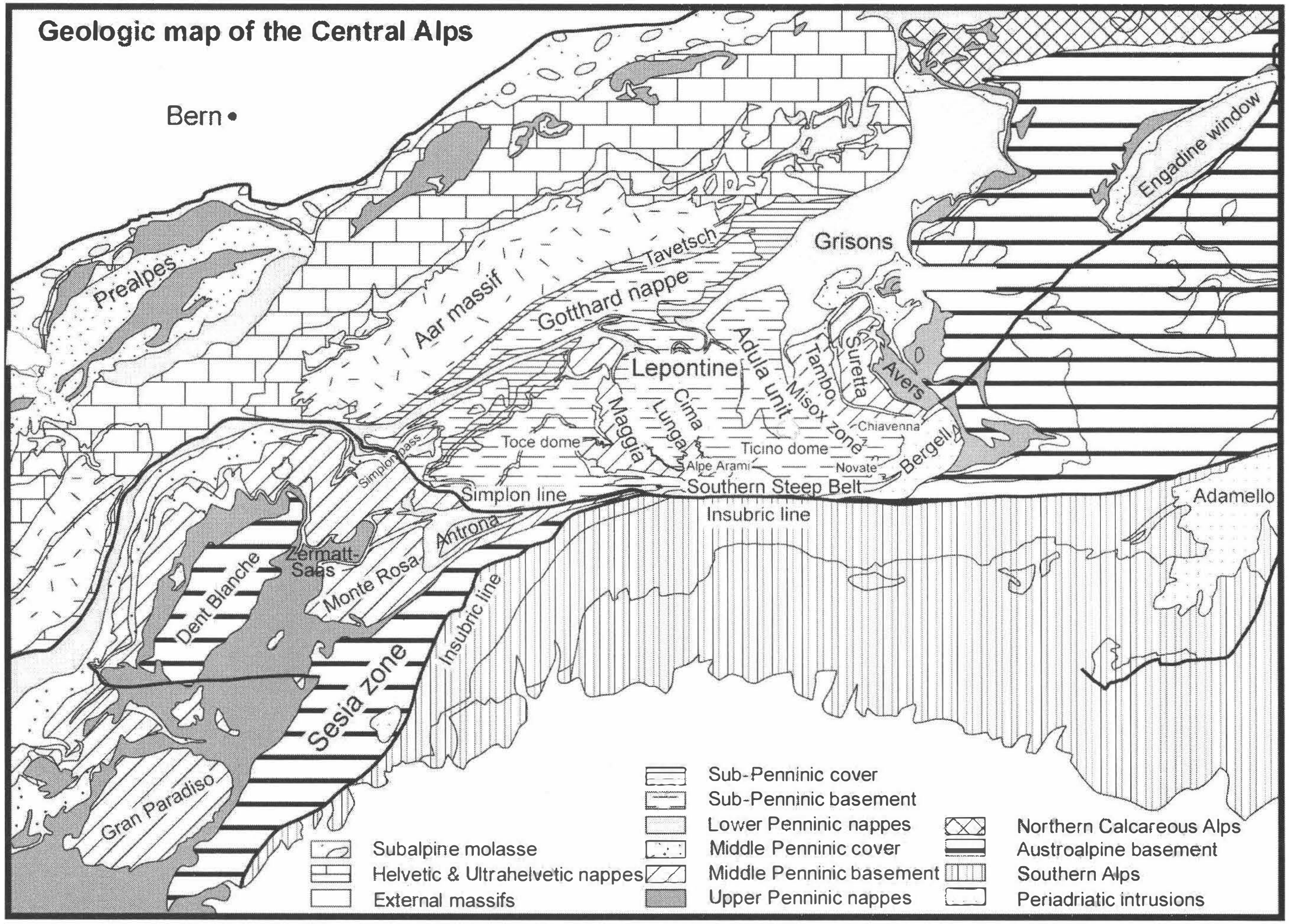

Fig. 1
Map showing locations and tectonic units to which the text refers.

This chapter presents the metamorphic evolution recognized in the Central Alps in chronological sequence, outlining the present state of understanding and indicating some of the limits. To keep the text concise, references to the essential primary data are far from exhaustive. Recent reviews are cited where available, and progress due to studies not treated in these is summarized in more detail. Still, it is not possible here to refer to all relevant studies produced in this classic orogen.

Pre-Alpine metamorphism in the Central Alps

At least two pre-Alpine cycles of orogenic metamorphism and deformation have been recognized in the External massifs and in the northernmost thrust sheets, all belonging to paleo-Europe. Following Proterozoic magmatism in a rift setting, Ordovician (Caledonian) high grade metamorphism and magmatism is well established, notably in the External Massifs, and the Permian (Variscan) magmatic and metamorphic imprint affected all of the basement units.

Caledonian orogeny: Case studies in the Central Alps (ABRECHT et al., 1991; ABRECHT & BIINO, 1994; BIINO, G., 1994; 1995; BIINO, G. G. et al., 1997) show eclogite facies and ± coeval granulite facies conditions. In the Gotthard and Tavetsch nappes for example, lawsonite grew on the prograde path, and eclogite formation peaked at $P_{max} \sim 2.4 \pm 0.3$ GPa and $T \sim 680 \pm 30$°C; the subsequent granulite and migmatite stages occurred at at 0.9-0.7 and 0.7-0.5 GPa, respectively, all at about the same temperature. This evolution reflects a collisional orogeny dated at ~460-464 Ma (OBERLI et al., 1994; GEBAUER et al., 1988). However, several stages of migmatite formation have been dated between 470 and 445 Ma, a period for which larger magmatic intrusions, both basic and granitic, are known from various units (as reviewed by SCHALTEGGER & GEBAUER, 1999). Amphibolite facies grade metamorphism and migmatites are widespread in the late Ordovician, as are large granitoid intrusives (MERCOLLI et al., 1994). To account for the tectono-metamorphic imprint during the Caledonian cycle, an active margin setting of a peri-Gondwana micro-continent has been invoked (VON RAUMER, 1998; VON RAUMER et al., 1999).

Variscan continent-continent collision: This cycle left its imprint both in the sedimentary record (Early Carboniferous synorogenic flysch: MATTE, 1986; FLÜGEL, 1990) and in widespread syn- and late-orogenic magmatism (360-320 Ma and 320-260 Ma, respectively). The metamorphic grade reached (low- to medium-P) amphibolite facies in the Central Alps. The overprint was thus less pronounced than in the Caledonian orogeny, but the effects of the two cycles are often difficult to distinguish. The spatial distribution of the Variscan phenomena suggests that continental terranes were accreted between the Silurian and the Devonian to the upper plate, now exposed e.g. in the External Massifs of the northern Central Alps. No such accretion is known from the (Variscan) lower plate, i.e. in Austroalpine and Southern Alpine units.

Alpine metamorphism in the Central Alps

Metamorphic assemblages in post-Variscan units, notably in post-Permian sedimentary sequences, are definitely attributable to the Tertiary Alpine cycles (NIGGLI, 1960). Yet even in such samples, evidence of a plurifacial Alpine metamorphism is fairly common in the Central Alps.

Similarly, this part of the Alpine orogen shows several generations of structural overprint (MILNES, 1974b; 1974a). Both the tectonic and metamorphic patterns in the Lepontine appear rather simple at first sight, concealing much of the complexity of their evolution. The nappe stack as a whole shows a central part which is relatively flat lying, despite two young, regional culminations (Ticino and Toce domes), whereas two steep belts delimit this central part both to the north and south. However, detailed studies of the structural evolution in several parts of the Lepontine nappe stack (e.g. northern Maggia-Lebendun: GRUJIC & MANCKTELOW, 1996; southern Simano-Adula: NAGEL et al., 2002b) indicate at least four phases of deformation, from early nappe-forming (D_1 and D_2; main schistosity and tight folds) to exhumation-related deformation, including the late-orogenic back-folding. Efforts to decipher the concomitant metamorphic evolution have recognized three discrete phases based on petrologic analysis and geochronology: (1) High-pressure assemblages of Eocene age are restricted to certain tectonic units; (2) a pervasive medium-pressure (Barrovian) overprint, connected with Oligocene nappe stacking, affected the Lepontine as a whole, postdates D_2 and either outlasted or was (locally) affected by D_3; (3) a far less pervasive, late-orogenic phase attained lower metamorphic grades, but was locally quite effective, notably related with hydrothermal fluids.

High-Pressure Relics in the Central Alps

a. Low- to medium-temperature HP rocks are found in several Middle- and South-Pennine units outside the Lepontine (amphibolite facies) belt, notably in the following:

- Several nappes, with different metamorphic patterns due to different tectonic histories, represent the Piemont-Ligurian domain in eastern part of the Central Alps. Regional metamorphic grade in these units was classically viewed (NABHOLZ, 1945) to increase from anchizonal conditions in the North (near Arosa, FERREIRO-MÄHLMANN, 1995) to biotite-greenschist facies to the south (Val Malenco, TROMMSDORFF & NIEVERGELT, 1983). However recent studies have recognized more complexity in the regional metamorphic distribution. In units mainly composed of mafic and ultramafic rocks (Arosa, Platta, Malenco), which have a thin Jurassic cover, overprinting under greenschist facies conditions only has been reported for the Alpine metamorphism dated between 70 and 100 Ma (PHILIPP, 1982; HANDY et al., 1996). On the other hand in the Avers unit, where the Piemont-Ligurian domain is mainly composed of Jurassic marbles and Cretaceous calcschists (equivalents to the Schistes Lustés in the Western Alps) with some MORB-type metabasalts, abundant evidence of HP metamorphism has been documented. Mineral assemblages such as Gln-Gt ± Ctd in metabasalts (OBERHÄNSLI, 1978), Gln-phengite in marbles, and Gt-Ctd in calcschists (WIDERKEHR, pers. com.) indicate Tertiary metamorphic conditions around 12 kbar and 400°C (RING, 1992a; 1992b). A major shear zone (Turba mylonite zone) separates Avers Bündnerschiefer from the Platta nappe (NIEVERGELT et al., 1996).
- To the East of the Lepontine, the Briançonnais microcontinent is reduced to two basement units (Tambo and Suretta nappes) and a metasedimentary nappe (Schams). The Tambo and Suretta nappes comprise polycyclic gneisses (NUSSBAUM et al., 1998) with Permian intrusives (Truzzo granite, Roffna porphyr) and monocyclic metasediments (strongly deformed and reduced Mesozoic series) – show Alpine assemblages which range from HP-greenschist / blueschist facies (in the N) to high-P amphibolite facies (in the S). Mineral assemblage data of blueschist facies conditions are scarce.

Phengite barometry yields P_{max} ~10-13 kbar (at T ~400°C in the N, ~550°C in the central part, BAUDIN & MARQUER, 1993; RING, 1992a) for the Tambo nappe, and 9-12 kbar (at 400-450°C, CHALLANDES, 1996; NUSSBAUM et al., 1998) for the Suretta nappe. However newly "rediscovered" occurrences of porphyroblasts of Ctd and Gt (STAUB, 1926, WIDERKEHR pers.com.) in Carbonifero-Permian cover of the Suretta nappe seem indicate that the previous estimates are only minimum conditions. In the Schams nappes, consisting mainly of limestones and breccias, the characteristic assemblage Phe-Chl-Qtz-Ab-Cal-Stp-Ep indicates lower greenschist facies metamorphism, with temperatures around 300-400°C (SCHREURS, 1995). However, according to their structural position (SCHMID et al., 1996), the Schams is likely to have experienced metamorphic conditions similar to those of the Tambo and Suretta nappes, i.e. blueschist facies between 45 and 50 Ma (CHALLANDES et al., 2003).

- Valaisan units (North Pennine Bündnerschiefer) to the NE and NW of the central Lepontine belt: A large volume shaly-calcareous-terrigenous sediments, is outcropping in northern Graubünden, i.e. at the northeastern border of the Lepontine dome. Here the Bündnerschiefer can be separated into two nappes, the Grava nappe below and the Tomül nappe above (STEINMANN, 1994). The main body of Bündnerschiefer was deposited in Cretaceous times (STEINMANN & STILLE, 1999) until the late Eocene (BAGNOUD et al., 1998). Basaltic intercalations of MORB composition (DÜRR et al., 1993; STEINMANN & STILLE, 1999) within Bündnerschiefer metasediments indicate that the Valaisan is floored by oceanic crust (TRÜMPY, 1980).

  Bündnerschiefer north and south of Thusis contain the typical mineral assemblage Ms + Pg + Na, K-mica + Chl + Qtz + Cal + organic matter ± Alb ± Dol (THUM & NABHOLZ, 1972). The same assemblage is also predominant in the Piz Aul area in front of the Adula nappe (KUPFERSCHMID, 1977) as well in Grava and Tomül nappes (STEINMANN, 1994; RAHN et al., 2002). Based on this, the metamorphic conditions experienced by Bündnerschiefer of northern Graubünden were generally interpreted as greenschist conditions. Rather than a metamorphic climax, these occurrences represent a strong retrograde overprint. Indeed, indications of an earlier high-pressure and low-temperature metamorphism have been found within the Bündnerschiefer as well within metabasaltic rocks. (Fe, Mg)-carpholite occurs as relic hair-like micro-fibres, included in quartz of quartz-carbonate segregations (GOFFÉ & OBERHÄNSLI, 1992) and chloritoid occurs within the rocks (OBERHÄNSLI et al., 1995). Glaucophane occurrences in the ophiolites are well known (OBERHÄNSLI, 1978; HEIM & SCHMIDT, 1891; NABHOLZ, 1945), but in contrast to the Engadine window, the Na-amphibole (OBERHÄNSLI, 1986) is richer in Mg and Fe^{3+} (Vals valley).

  For carpholite-bearing rocks devoid of chloritoid, calculated pressures range from 10 to 12 kbar and temperatures from 350 to 375°C, whereas for carpholite + chloritoid-bearing rocks, temperatures estimated from the Fe-Mg partitioning between chloritoid and chlorite range from 360 to 400°C, and pressures estimated range from 12 and 14 kbar (BOUSQUET et al., 2002). In the HP metamorphic unit, two types of P-T paths are observed. In the (Fe, Mg)-carpholite zone without chloritoid where the carpholite fibers are well preserved, maximum P-T conditions are ~11-12 kbar and 350°C (BOUSQUET et al., 1998). The preservation of carpholite and the absence of imply a decompression path that did not cross the equilibrium.

The retrograde P-T path must have been cold and fast enough to metastably preserve carpholite but not aragonite (GILLET & GOFFÉ, 1988). In addition, partially replaced carpholite occurs in association with chloritoid, implying a warmer decompressional P-T path. Associated with these blueschists, eclogite (with P > 12 kbar at T ~510 ± 50°C) is known from a single locality in the (southernmost) Misox Zone (OBERHÄNSLI, 1994).

These calculated P-T conditions confirm an increase in metamorphic grade from the northeast to the southwest, as reported by NABHOLZ (1945).

- Where these accretionary wedge sequences attained amphibolite facies conditions, i.e. in the central Lepontine area, HP-assemblages have not been found so far. However, such assemblages ((Fe, Mg)-carpholite – chloritoid) have recently been discovered both to the east (OBERHÄNSLI et al., 2004) and west of the Lepontine amphibolite facies region, hence it seems likely that these had existed also in the central portion prior to the strong Barrovian overprint.

b. Alpine eclogite facies remnants in the central Lepontine area appear to be restricted to tectonic mélange units. They are isolated occurrences in a belt that includes relics of variegated high grade metamorphism, from granulite facies to eclogite to (typically HP) amphibolite facies. Collectively these are thought to represent remnants of a tectonic accretion channel (TAC: ENGI et al., 2001), which had developed along the convergent plate boundary during Alpine subduction, collision, and extrusion. Classic eclogite (and garnet peridotite) localities (TROMMSDORFF, 1990) are in the Adula nappe (e.g. Trescolmen) and the Cima Lunga unit (e.g. Gagnone), but we have recently found eclogite relics in several additional units, including the Mergoscia-Arbedo zone and the Someo-Orselina zone. All of these TAC units (Fig. 2) constitute tectonic mélanges, i.e. highly deformed and imbricated slices of various gneiss types, trails of clastic metasediments with lenses of marble, sparse ultramafic rocks, and dismembered mafic rocks. The metamorphic grade varies greatly within and between the different TAC units, and the patterns are far from fully understood. For example, a regional PT-gradient (HEINRICH, 1986; MEYRE et al., 1997; 1999) is evident in the Adula nappe, with eclogite stage conditions increasing from the north (1.0-1.5 GPa at 500 ± 50°C) to the south (3.0-3.6 GPa at 800-900°C). Although the Adula nappe is made up of an imbricated series of thin slices, at least the northern and central parts shows a consistent metamorphic field gradient of 20 ± 5 MPa/km and 9.6 ± 2.0°/km over the frontal 25 km of the nappe (DALE & HOLLAND, 2003). This field gradient links Eocene HP-assemblages formed within the TAC, which was dipping ~45°S, and this terrane apparently behaved as a coherent tectonic unit along the exhumation path.

Metagabbroic kyanite eclogite and metabasaltic eclogite fragments occur in other TAC units as well, and PT-conditions show substantial variation among individual HP-fragments (Fig. 3), both in their P_{max} and the decompression-cooling paths they experienced (ENGI et al., 2001; BROUWER & ENGI, 2004). Internal mobility within the TAC during its extrusion is also evident in the southern parts of the Adula nappe, based on structural and petrological data (NAGEL et al., 2002b; DALE & HOLLAND, 2003). Most prominent among the HP-fragments are the classical localities of Cima di Gagnone and Alpe Arami which belong, respectively, to the Cima Lunga unit and the Mergoscia-Arbedo zone. Whereas metarodingites show a serpentinization stage prior to the HP-metamorphism for the former (EVANS & TROMMSDORFF, 1978; PFIFFNER & TROMMSDORFF, 1997), this is not the case for any of the HP-bodies known within the latter.

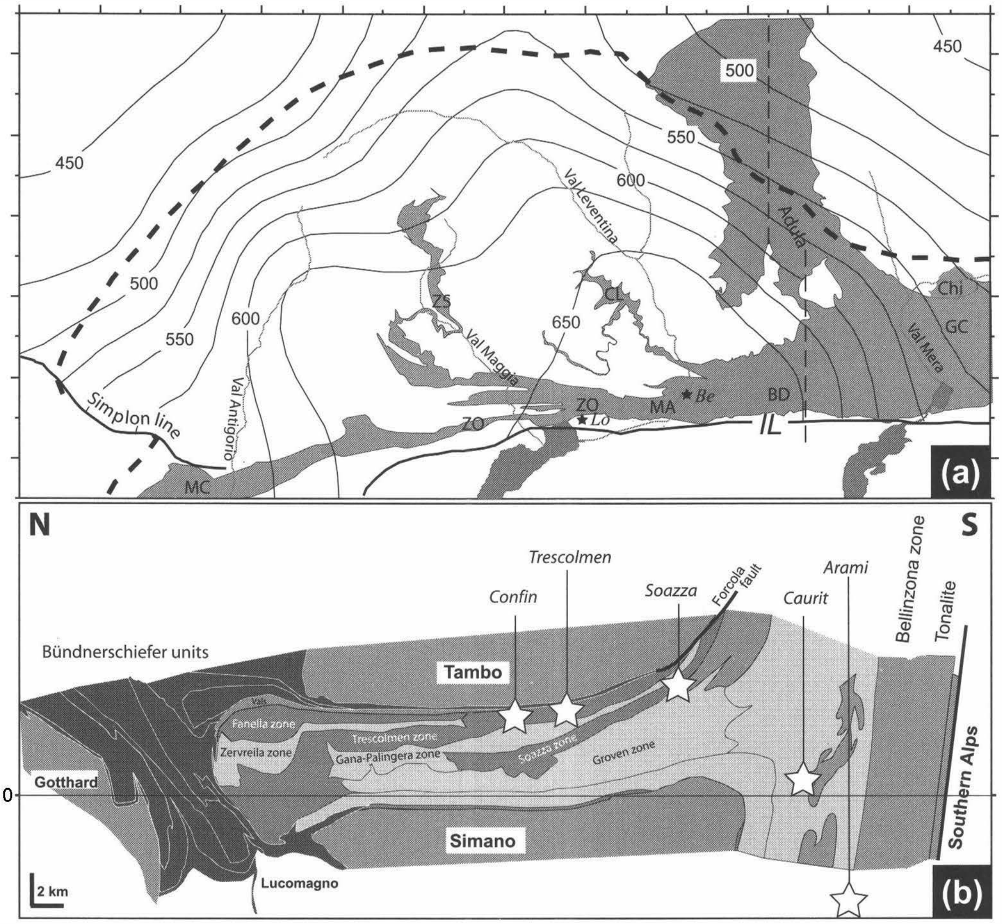

Fig. 2a

Map of the tectonic mélange belt in the Central Alps interpreted to represent a portion of the tectonic accretion channel (TAC). Labels refer to some of the more prominent subunits of this belt classically mapped as individual "zones" (BD: Bellinzona-Dascio zone, CL: Cima Lunga unit, CM: Camughera-Moncucco unit, GC: Gruf complex, Chi: Chiavenna ophiolite, MA: Mergoscia-Arbedo zone, ZS: Someo zone, ZO: Orselina zone; stars mark some towns; Be: Bellinzona; Lo: Locarno). Trace of synthetic profile for Fig. 2b and isotherms from Fig. 4b are also shown.

Fig. 2b

Schematic Profile through the central Lepontine Alps. The classic Adula thrust sheet is a nappe-shaped body comprising a number of these zones (various shades of grey). Internal slices in the Adula nappe after JENNY et al. (1923), KÜNDIG (1926), and NAGEL et al. (2002). Occurrences of relic eclogites (stars indicate some of the localities) are restricted to the TAC. Its internal structure is outlined, with mapped zones representing slices of imbricated mélange sheets, each comprising a distinct spectrum of rock types. Eclogite relics are missing in the basal part of the Adula nappe, which is thus tentatively separated from the TAC zones in the upper part. Bündnerschiefer units comprise several slices (after LÖW, 1987) of the Alpine accretionary prism.

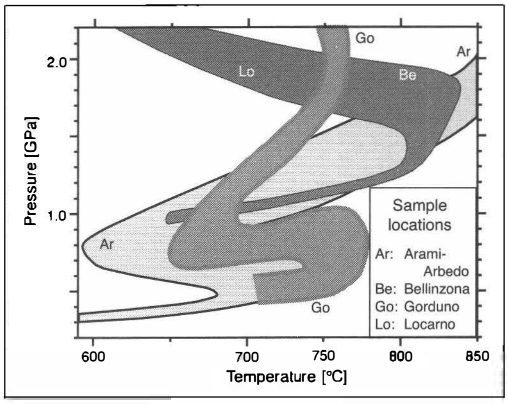

Fig. 3
P-T paths documented for various lenses within the TAC (BROUWER, 2000; TÓTH et al., 2000; ENGI et al., 2001; GRANDJEAN, 2001; NIMIS & TROMMSDORFF, 2001; BROUWER & ENGI, 2004). The HP-route documented for each body may differ substantially from those of nearby lenses, but their P-T paths converge at mid-crustal levels, indicating a fairly uniform (coherent ?) exhumation of the TAC during its final emplacement.

Some authors have suggested UHP (ultra-high pressures) for the early evolution of garnet peridotite from Alpe Arami (DOBRZHINETSKAYA et al., 1996: > 300 km; BRENKER & BREY, 1997: > 5 GPa; BOZHILOV et al., 1999: > 8 GPa; OLKER et al., 2003: 5.9 GPa, 1180°C), whereas others derived conditions (e.g. NIMIS & TROMMSDORFF, 2001: 3.2 GPa, 840°C) much more in line with those found for other Alpine garnet lherzolite and associated eclogite lenses from the southern parts of the TAC (e.g. NIMIS et al., 1999: 3.0-3.2 GPa, 740-840°C). The controversy regarding the highest pressures is unresolved at this time. It is possible (but not clear) that the reported UHP conditions may document an early stage within the Mantle. Since comparable pressures have neither been reported for associated eclogites nor metapelites (and no coesite or diamond relics have been found to date), Arami may not be a relevant constraint the esimate the maximum depth reached by the TAC.
The central portion of the mélange unit interpreted to represent an Alpine TAC (shown as a variegated facies unit on the Map of Alpine Metamorphism), is definitely delimited from the Pennine nappes adjacent to the north. Towards the eastern and western boundary of this belt, the separation is more tentative at this time. The TAC does not appear to extend beyond the Bergell intrusive sheet in the E, but the Gruf unit (with Alpine granulite facies relics) and Chiavenna ophiolite are interpreted as belonging to the TAC. Similarly, in the W the Monte Rosa nappe is a definite limit, but the Antrona and Moncucco-Camughera units are tentatively considered to be part of the TAC.

c. Age constraints for the HP-stage in the Central Alps show that Early Tertiary closure of the Piemont-Ligurian basin lead to accretion of a sedimentary wedge (South Pennine Bündnerschiefer) during the Paleocene, with subduction of the Briançonnais microcontinent following by early Eocene. The Tambo and Suretta terranes were welded to Apulia, and a coherent TAC formed in their footwall during the subsequent closure (50-47 Ma, SCHMID et al., 1996) of the Valais basin, where sedimentation continued into the Eocene (LIHOU, 1995; 1996). Eclogite formation (FROITZHEIM et al., 1996) in TAC units was initially dated between ~43-36 Ma for fragments from both Arami and Gagnone (BECKER, 1993; GEBAUER, 1996; 1999), but recent data for other fragments in the Central Alpine TAC indicates eclogite facies conditions in an age range from ~55 to 35 Ma (BROUWER et al., 2003a; 2003b). Exhumation from depths of >100 km to the Barrovian overprint (25-15 km) by 32 Ma implies a short time interval for the very rapid extrusion of parts of the TAC to mid-crustal levels.

The Oligo-/Micene Lepontine Belt

A relatively simple zonal pattern in the metamorphic field gradient (Fig. 4a) has long been recognized in the Lepontine Alps. Mineral zone boundaries and metamorphic reaction isograds (see recent review by FREY & FERREIRO MÄHLMANN, 1999) outline a classical Barrovian belt. Conditions range from anchimetamorphic – in the northern, most external parts of the orogen – to sillimanite-Kfsp / grade in the southern, most internal portion of the dome. Abundant late-orogenic migmatites occur within the Southern Steep Belt. Immediately to the South of this shear belt, the core part of the Alpine orogen is truncated by the Insubric Line, separating the Central Alps from the Southern Alps. The latter show but incipient Alpine metamorphism.

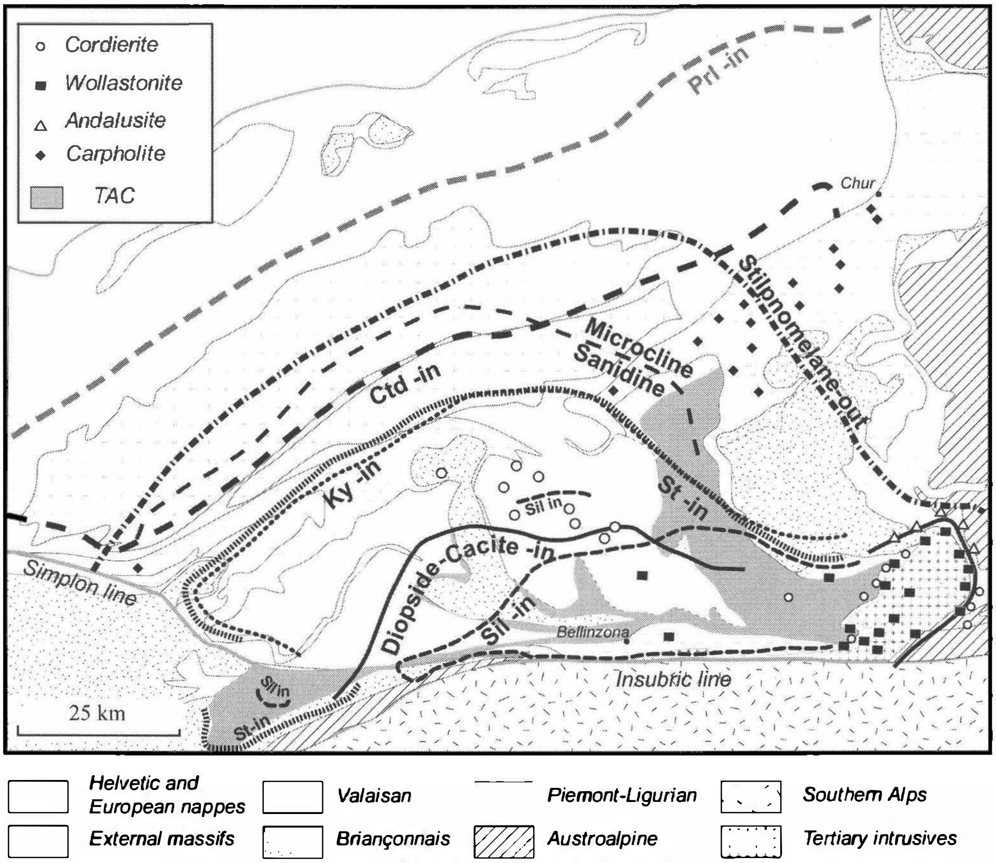

Fig. 4a

Select isograds (solid curves) and mineral zone boundaries (dashed curves) of Alpine metamorphism in the Central Alps. Updated from FREY & FERREIRO MÄHLMANN (1999), based on NIGGLI & NIGGLI (1965), TROMMSDORFF (1980), BERNOTAT & BAMBAUER (1982), IROUSCHEK (1983) and FREY (1987); with additions from KELLER (2004) and data on Mg-Fe carpholite from GOFFÉ & OBERHÄNSLI (1992) and BOUSQUET (unpubl.). SF: Simplon fault, CF: Centovalli fault.

A wealth of detail has been established regarding the metamorphic overprint in the Central Alps, manifested by Barrovian mineral zones of stilpnomelane, chloritoid, staurolite and kyanite, as well as (fibrolitic) sillimanite (NIGGLI & NIGGLI, 1965; FREY & FERREIRO MÄHLMANN, 1999). It should be noted that the first appearance of any one of these aluminous phases does not reflect one specific irreversible reaction, and such a mineral zone boundary thus does not constitute a metamorphic isograd sensu stricto.

For example, in the Adula and Simano nappe, NAGEL et al. (2002a) showed that several paragonite breakdown reactions lead to the appearance of staurolite (as well as kyanite and sillimanite), whereas in the Lucomagno area, FREY (1974) found staurolite to grow at the expense of chloritoid. The former reactions took place during (±isothermal) decompression, the latter along a prograde burial path. Nevertheless, at least the medium and upper amphibolite facies, mineral zone boundaries for metapelites and ultramafic rocks (TROMMSDORFF & EVANS, 1969; 1974; NAGEL et al., 2002a) do outline a zonal pattern which corresponds rather closely to proper mineral (reaction) isograds, such as tremolite-calcite and diopside-calcite mapped for siliceous dolomite marbles by TROMMSDORFF (1966).

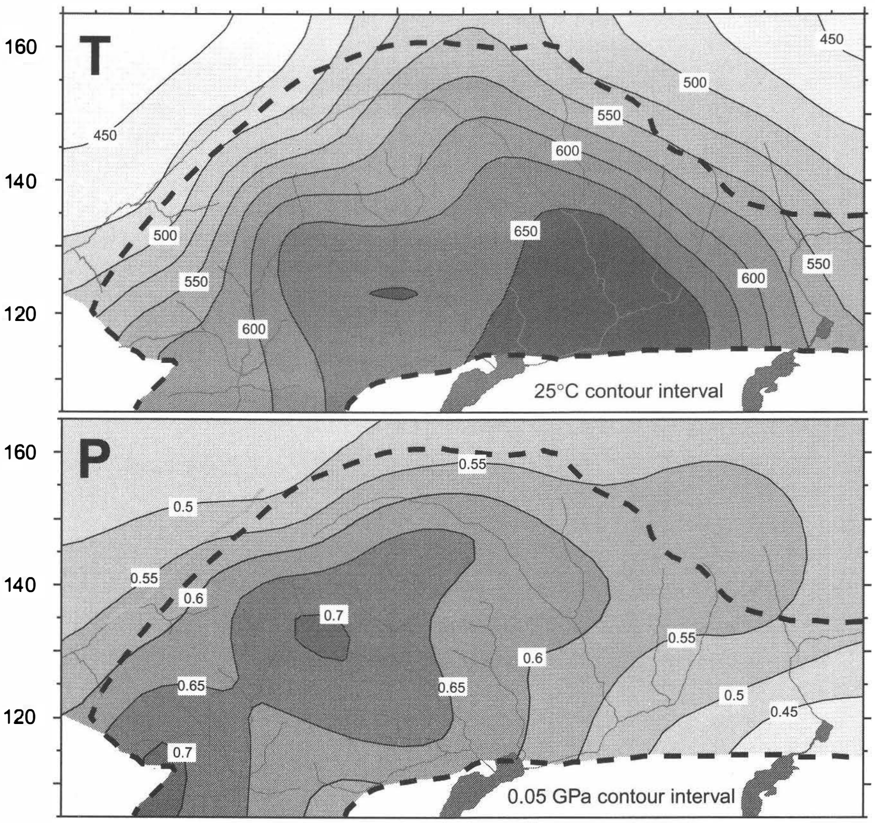

Fig. 4b/c

Map of isotherms and isobars for the Barrovian overprint in the Lepontine (updated from ENGI et al., 1995; TODD & ENGI, 1997), reflecting conditions near T_{max} and $P_{(T_{max})}$.

The regional thermal and baric structure of the Lepontine belt (Fig. 4b/c), combined with recently determined PTt-paths from several tectonic units and mineral age data, indicate that the mid-Tertiary overprint which produced the Barrovian structure was diachronous by about 7 My. The thermal peak was first reached in the Southern Steep Belt, about 28 Ma ago, at pressures of 0.5-0.55 GPa only. During this late stage of decompression, fluid-assisted partial melting occurred (BURRI, 2004), producing up to ~30 vol-% leucosomes, which are variably deformed (by D_3 backfolding). Intrusive ages for the Novate stock, a small S-type granite that segregated late-stage partial melts, provide another age constraint for the migmatisation (~24 Ma, LIATI et al., 2000). This magmatism is distinct from and clearly postdates the intrusion of the Bergell granodiorite and the associated tonalite sheet (VON BLANCKENBURG, 1992; OBERLI et al., 2004). In units further to the north, i.e. the central parts of the Lepontine, the thermal peak appears to have been reached at successively later times, between 26 and ~21 Ma ago, but here the thermal climax was reached at greater depths (P = 0.6-0.75 GPa). At the northern margin of the Lepontine amphibolite facies belt, T_{max} and P(at T_{max}) are lower (Fig. 2), but the age pattern remains unclear (HUNZIKER et al., 1992; ENGI et al., 1995). Ages between 42 and 16 Ma have been reported on the basis of different mineral chronometers, and it seems likely that these represent a mix of signals (and noise) recorded over 2-3 stages of evolution, i.e. the early HP phase (?), a prograde medium-pressure subduction phase, and the Barrovian overprint following emplacement of the TAC units and final exhumation of the nappe stack.

During this progressive exhumation process (NAGEL et al., 2002b) TAC-units with an ealier eclogite facies imprint were variably overprinted under amphibolite facies conditions (e.g. HEINRICH, 1982; MEYRE et al., 1999). The extent of this overprint was strongly dependent on the availability of hydrous fluids and localized deformation. Tectonic fragments now contained in the TAC-units in many cases show no early HP segment in their PT-paths, whereas nearby lenses differ strongly in the P_{max} and/or T(at P_{max}) they recorded (ENGI et al., 2001; NAGEL et al., 2002b), it is difficult to infer at what stage the accretion channel consolidated to a coherent tectonic unit. While much remains to be investigated, it certainly appears from the tectonic location and internal characteristics of this mélange unit that it played a crucial role in the tectono-metamorphic evolution of the Central Alps. Thermal modelling (ROSELLE et al., 2002) indicates that the relatively high temperatures reached during the regional Barrovian metamorphism can be explained by considering the dominantly upper crustal contents of the TAC, which in the Central Alps has an average heat production of 2.67 μW m^{-3}. Recent reports (ÁBALOS et al., 2003; LÓPEZ SÁNCHEZ-VIZCAÍNO et al., 2003) indicate that tectonic elements of similar character as the Alpine TAC are important in other collisional belts as well.

In the section of Lepontine between Valle Mera and Locarno, the Southern Steep Belt of the Central Alps is terminated to the south by the Insubric Line, and TAC units, in part intruded by the Bergell tonalite sheet, form the limit to the Southern Alps. To the West of Locarno, however, the Insubric Line swings SW, whereas the Steep Belt continues in a westward direction, being cut in part by the Centovalli Line, an important late-orogenic E-W lineament with largely brittle character. In between the southernmost TAC-units and the Insubric Line two thrust sheets emerge, the Monte Rosa and the Sesia nappe, gaining in thickness towards the west. The Barrovian overprint in units south of the Centovalli Line rapidly decays, and the transition from greenschist facies to amphibolite facies runs nearly E-W.

However, in contrast to areas in the SSB east of Locarno the tectonic units lying immediately south of the TAC units do show Barrovian overprint. Quenching of the heat advected by the Central Alpine belt was directly against the Southern Alps in the eastern section, but against the Sesia and Ivrea bodies in the western section of the SSB. The spacing of isotherms (Fig. 4b) gets notably much wider in the west. This is likely to reflect the dextral transpressional exhumation, during which the the southern block was successively heated by the hottest portion of the northern block and, as the transfer of heat from the hot Central Alpine block to the cool southern block was most effective initially, leading to rapid quenching in the eastern part of the Central Alps, whereas the thermal quench was less pronounced in their western portion. This topic is further elaborated in the chapter by BOUSQUET et al. (2004).

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EXPLANATORY NOTES TO THE MAP: METAMORPHIC STRUCTURE OF THE ALPS METAMORPHIC EVOLUTION OF THE EASTERN ALPS

by

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1. Introduction

The Eastern Alps are the product of two orogenies, a Cretaceous orogeny followed by a Tertiary one (FROITZHEIM et al., 1996). The former is related to the closure of an embayment of the Neotethys ocean into Apulia (Meliata ocean), the latter is due to the closure of the Alpine Tethys oceans between Apulia and Europe.

The result of the orogenic movement is a complex nappe stack, which is built up from north to south and from bottom to the top by the following units (Plate 1 in SCHMID et al., 2004): The proximal parts of the Jurassic to Cretaceous European margin built up the northern Alpine foreland and the Helvetic nappes, whereas the distal margin is represented by the Subpenninic nappes. The Penninic nappes comprise the Piemont-Ligurian and Valais ocean (Alpine Tethys) and the Briançonnais Terrain. Apulia consists of the northern Austroalpine nappes and the Southern Alpine unit (STAMPFLI & MOSAR, 1999). Remnants of the Neotethys embayment occur as slices within the eastern part of the Austroalpine nappe stack. Both orogenic events are accompanied by regional metamorphism of variable extent and P-T conditions. The Cretaceous (Eo-Alpine) metamorphism effects mainly the Austroalpine Nappes, the Penninic domain by the Tertiary metamorphism, some units of the Lower Austroalpine Nappes show signs of both events.

2. Metamorphic evolution of the Eastern Alps

2.1. Geological Framework of the Eastern Alps

In the Eastern Alps (Plate 1 in SCHMID et al., 2004) the Jurassic to Cretaceous European margin is represented by the Helvetic and Ultrahelvetic Nappes composed of Mesozoic sedimentary series and by the Subpenninic nappes consisting of orthogneisses with remnants of roof pendants (Altes Dach), Paleozoic metasediments and a transgressive Mesozoic cover. The Helvetic and Ultrahelvetic Nappes built up the northern foothills of the orogen, whereas the Subpenninic Nappes occur in the Tauern Window in the south.

The Penninic nappes are present along the northern margin of the Alps and within the Lower Engadin Window, Tauern Window, and Rechnitz Window Group. Cretaceous ophiolitic fragments overlain by Cretaceous to Tertiary (Lower Engadine Window) calcareous schists as well as flysch sediments (Rhenodanubian flysch) of the Valais ocean form the Lower Penninic Nappes. The eastern oftshoots of the Middle Penninic Nappes reach until the Lower Engadine Window. They consist of a continental basement with a Mesozoic cover. The Upper Penninic Nappes (Piemont-Ligurian ocean) are characterised by slices of subcontinental mantle and oceanic crust in connection with Jurassic radiolarites and Cretaceous to Tertiary calcareous schists.

The Austroalpine nappes are composed of crustal material with a complex Phanerozoic history. They can be subdivided in a Lower and an Upper Austroalpine unit. The former shows a remarkable reworking related to the opening and closure of the Piemont-Ligurian and Valais ocean, whereas the internal structure of the latter is due to the closure of the Tethys embayment. Coming from the north the Upper Austroalpine unit is built up by Mesozoic sedimentary sequences of the Northern Calcareous Alps, Paleozoic metasediments and metavolcanics of the Graywacke zone and the crystalline basement units with remnants of Paleozoic and Mesozoic metasediments. The crystalline basement can be subdivided into four parts: The lowermost Silvretta-Seckau nappe system is predominantly consisting of a deeply eroded Variscan metamorphic crust with a partly preserved Mesozoic cover (NEUBAUER et al., 1999a, NEUBAUER, 2002). The overlying Wölz-Koralpe nappe system is built up exclusively by pre-Mesozoic rocks and represents an extruding metamorphic wegde. Above this wedge the Ötztal-Bundschuh and the Gurktal-Drauzug nappe system are present. To the south of the Periadriatic lineament the Southern Alpine unit is located. The nappe systems above the wedge as well as the Southern Alpine unit are composed of crystalline basement, Paleozoic metasedimentary rocks and Permomesozoic cover sequences.

Nearly all nappe units contain metasedimentary sequences and/or metabasaltic rocks of Mesozoic age. During the Alpine tectonometamorphic events prograde assemblages formed in these rocks, defining the grade of the Alpine metamorphic imprints. However, large parts of the Austroalpine nappes, especially those of the Wölz-Koralpe nappe system lack prograde sequences, but show complex polyphase microstructures. It is not always easy to distinguish between several metamorphic events, which reach sometimes similar conditions. Therefore, due to missing geochronological data, different individual metamorphic events including the Variscan or Permian event, were sometimes mixed up in the older literature.

2.2. Pre-alpine metamorphic history of the Austroalpine Unit

In the Austroalpine unit two regional Palaeozoic metamorphic imprints are well documented. In the Penninic and Subpenninic unit of the Eastern Alps only one is known up to now and this one is restricted to the basement of the Tauern Window.

2.2.1. Variscan tectonometamorphic event

Pre-Alpine metamorphic basement units are exposed within different continental microplates of the Eastern Alps: the Subpenninic, Penninic, Austroalpine and Southalpine units. They show varriable metamorphic imprints due to the variety of metamorphic facies and age of metamorphism. These imprints are interpreted to result from accretion of various units to the active Laurasian continental margin.

The Variscan metamorphic event was induced by the collision of Africa, Baltica, Laurentia and intervening microplates (TAIT et al., 1997). A collision related LT/HP imprint occurred prior to 350 Ma. The thermal metamorphic peak was reached at about 340 Ma at medium pressure conditions. Typical Variscan cooling ages are about 310 Ma (MILLER & THÖNI; 1995, NEUBAUER et al. 1999a; THÖNI, 1999).

The Subpenninic basement exposed within the Tauern Window is largely overprinted by Variscan migmatite-grade metamorphism associated with intrusions of Variscan granites. Rare eclogites of Silurian age predate migmatite formation. The Austroalpine basement units vary in metamorphic grade and timing of metamorphism ranging from greenschist to granulite facies conditions. Only a Variscan greenschist metamorphic overprint is recorded in the eastern part of the Southalpine unit.

2.2.2. Permo-Triassic tectono-thermal event

The Permo-Triassic imprint reflects lithospheric extension after the late Variscan orogenic collapse. It may be due to the anticlockwise rotation of Africa and the southern part of the Apulian microplate with respect to Eurasia and the northern part of the Apulian microplate and caused extension within the Austroalpine and South Alpine realm. Accompanied thinning of the lithosphere resulted in a high temperature metamorphic imprint (HT/LP) (SCHUSTER et al., 2001).

The Permo-Triassic imprint is widespread in the Austroalpine unit (Fig. 1) and affects pre-Permian rocks of different metamorphic grade (HABLER & THÖNI, 2001; SCHUSTER et al., 2001). Well preserved Permo-Triassic metamorphic rocks occur in the Gurktal-Drauzug nappe system between the southern border of Alpine metamorphism (SAM, HOINKES et al. 1999) and the Periadriatic Lineament, as well as in the western part of the Silvretta-Seckau nappe system. Similar lithologies with an Eo-Alpine overprint of different grade are present in the Wölz-Koralpe nappe system.

Areas with well preserved Permo-Triassic HT/LP lithologies south of the SAM

Well preserved Permo-Triassic HT/LP assemblages occur within more or less complete sections of Permo-Triassic crustal fragments up to c. 15 km structural depth. They comprise of a upper and middle continental crust and their Permo-Triassic sedimentary cover sequencies with intercalations of Lower Permian quartz-porphyries. In the crust a continous increase of the metamorphic grade up to high amphibolite facies lithologies with local anatexis can be identified by

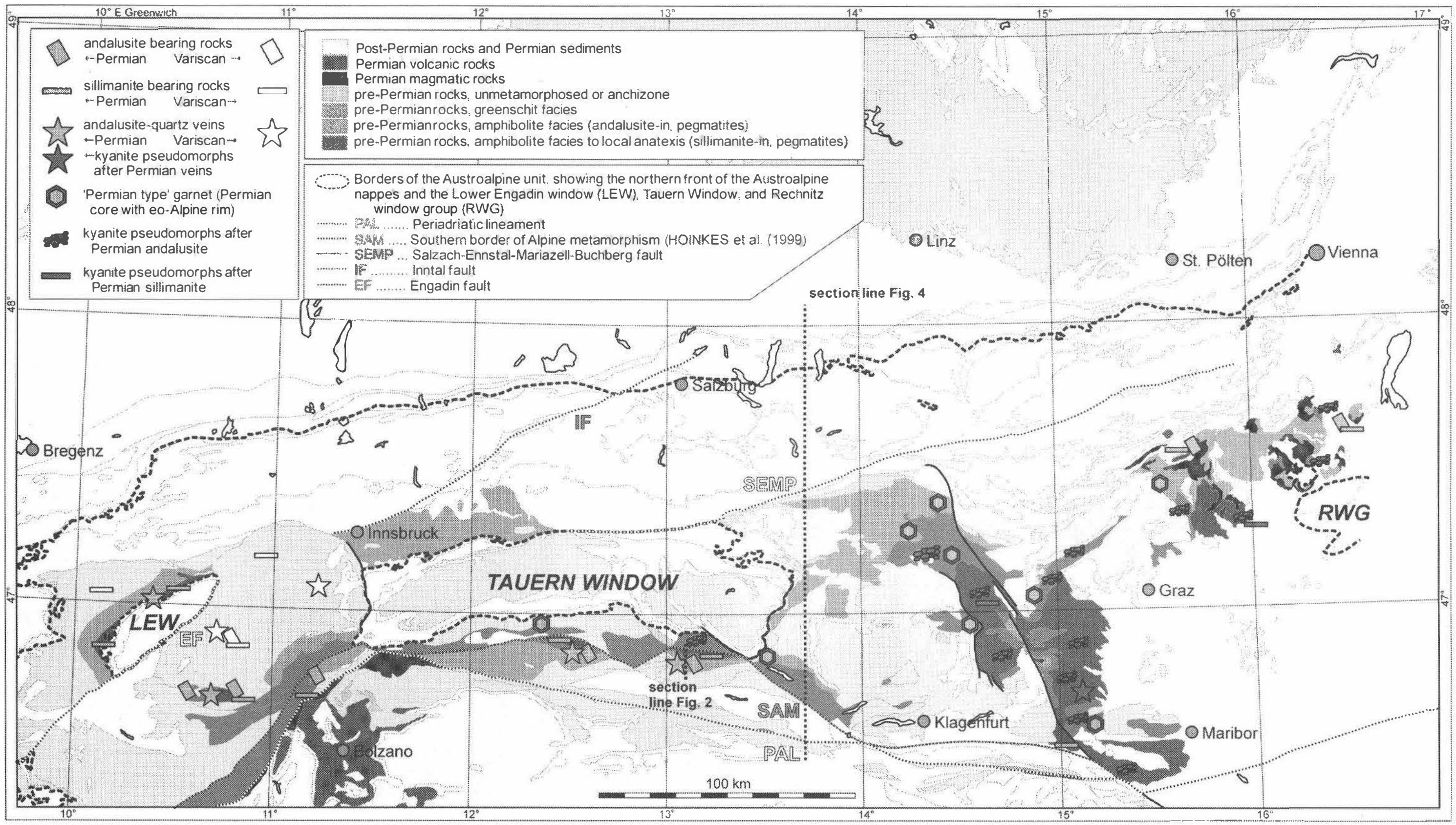

Fig. 1

Tectonic map of the Eastern Alps showing the distribution of the Permo-Triassic metamorphic imprint. Additionally the section lines of the transsects in Fig. 2 and Fig. 4 are given.

decreasing cooling ages, different HT/LP assemblages and the occurrence of Permian magmatic rocks. The structurally deepest parts are outcropping along Tertiary structures, e.g. along the Defereggen-Antholz-Vals fault, the Ragga-Teuchl fault or the thrust plane along the northwestern margin of the Lower Engadin Window.

One of the most complete sections is preserved in the Kreuzeck and Goldeck Mountains (Fig. 2). In this profile a Permo-Triassic event is overprinting Variscan metamorphic rock sequences of different metamorphic grade. In the tectonic higher units (south of the profile shown in Fig. 2), white mica Ar-Ar ages of ~310 Ma reflect post-Variscan cooling. The Variscan structures and assemblages are well preserved. In the upper part of the Strieden Complex post-deformation mica growth with respect to the Variscan structures can be observed, the white mica Ar-Ar ages range from 290 in the south to 260 Ma in the north. Below a zone with andalusite bearing lithologies occurs (HOKE, 1990). Andalusite, forming up to several centimetres large porphyroblasts, is frequently found within layers of Al-rich metapelites (24.9-26.9 wt% Al_2O_3) with a low X_{Mg} (0.19-0.23). Together with plagioclase and coarse-grained biotite flakes andalusite is overgrowing the Variscan microfabrics and porphyroblasts of staurolite and garnet. Andalusite is formed by the breakdown of chlorite (Chl + Ms ⇔ And + Bt + Qtz + H_2O) and paragonite (Pg + Qtz ⇔ Ab + And + H_2O). Furthermore, there are lithologies where staurolite is present only as small and dismembered inclusions with identical optical orientation within the andalusite porphyroblasts. In this case the andalusite growth is due to the breakdown of staurolite (St + Ms + Qtz ⇔ And + Bt + H_2O). Coarse-grained veins with mineral assemblages of Qtz + And + Ms ± Pl ± Ilm are crosscutting the Variscan foliation of the andalusite-bearing schists. Within these veins andalusite idioblasts up to 20 cm in length occur. Within deformation zones they are ductily deformed and fibrolitic sillimanite was growing within highly sheared areas. Ar-Ar muscovite ages of the andalusite-zone are in the range of 200-230 Ma.

In the lowermost part of the andalusite-zone isolated pegmatites appear, whereas pegmatites are frequent in the sillimanite-zone below. In metapelites sillimanite occurs within biotite-rich layers and as millimetre-sized patchy pseudomorphs, which often contain relics of garnet or staurolite covered by quartz. Locally plagioclase porphyroblasts up to 1 cm in size are growing. With structural depth the content of muscovite is decreasing. In the lowermost part anatectic mobilisates composed of Qtz + Pl + KFsp ± Bt ± Sil are present. Obviously sillimanite is formed by the successive breakdown of paragonite (Pg + Qtz ⇔ Ab + Sil + H_2O), staurolite, garnet (Grt + Ms ⇔ Sil + Bt + Qtz + H_2O) and muscovite (Ms + Qtz ⇔ Sil + L). Together with the continuous change in the mineralogy a syn-metamorphic foliation becomes more prominent with structural depth. In the lowermost part the Variscan mineral assemblages and microstructures are nearly totally annealed. The pegmatites exhibit magmatic assemblages of Kfsp + Pl + Qtz + Ms + Turm ± Grt. Most of them are concordant or slightly discordant with a weak ductile deformation. Some are folded by the syn-metamorphic schistosity. Magmatic crystallisation ages of the pegmatites yielded 260-285 Ma. The pegmatites are obviously related to the HT/LP event, because they occur only in the lowermost andalusite-zone and within the sillimanite-zone. Additionally spodumene-bearing pegmatites are known. Typical Ar-Ar muscovite ages of the sillimanite zone are ~190 Ma.

In the NKFMASH grid (SPEAR, 1993) the following assemblages characterise the Permo-Triassic imprint (Fig. 3): And + Bt + Ms + Pl (500-570°C, < 0.35 GPa), Sil + Bt + Ms + Pl (550-650°C, 0.3-0.45 GPa), Sil + Bt + Pl + melt (> 650 °C, < 0.45 GPa).

These assemblages define an elevated metamorphic gradient of ~40°C/km. According to the age data on the synmetamorphic pegmatites the metamorphic peak occurred at ~270 Ma. After 270 Ma. the rock pile was not exhumed but cooled down to heat flow contitions of ~25°C/km, which was reached at ~190 Ma (SCHUSTER et al., 2001).

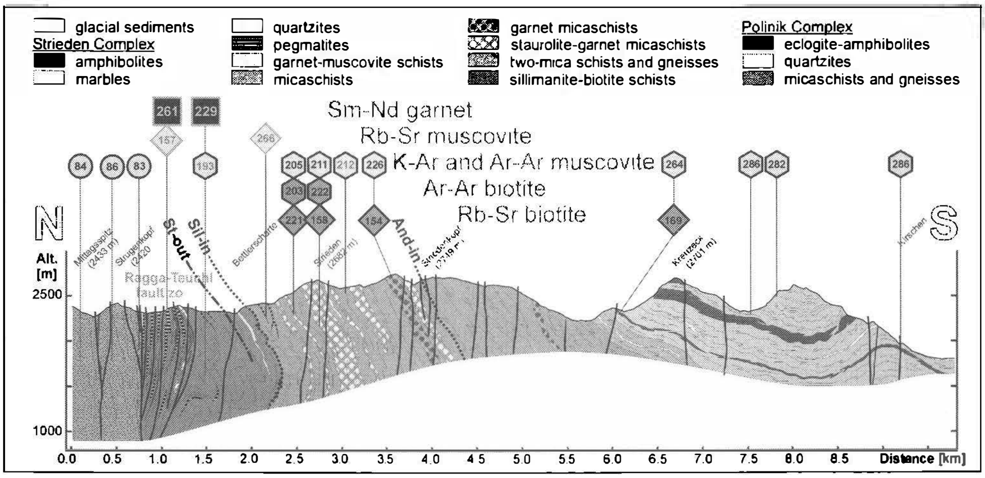

Fig. 2

Transsect through the Kreuzeck mountains (Carinthia/Austria). The Polinik Complex to the north of the Tertiary Ragga-Teuchl fault zone experienced an eclogite and high-amphibolite facies imprint during the Eo-Alpine thermal event. Typical K-Ar muscovite cooling ages are about 85 Ma. The Strieden Complex to the south of the fault zone is characterised by an anchizonal to lowermost greenschist facies Eo-Alpine imprint. Therefor the Permo-Triassic thermal imprint can be studied. In the structural lowermost part sillimanite is the typical alumosilicate phase, whereas above andalusite can be found. Ar-Ar muscovite ages show increasing values towards the top.

Permo-Triassic HT/LP lithologies north of the SAM

In the western part of the Eastern Alps a Permian to middle Cretaceous diastathermal metamorphism has been reported. During Permian and lower Triassic times a high heat flow caused a near surface geothermal gradient of ~70°C/km and burial temperatures up to 300°C (FERREIRO-MÄHLMANN, 1995, 1996).

Within the Wölz-Koralpe Nappe system the units with the highest Eo-Alpine metamorphic grade also exhibit the most intense Permo-Triassic imprint. The latter can be identified by the occurrence of Permian garnet cores within polyphase garnet crystals, characteristic kyanite aggregates pseudomorphosed after andalusite and sillimanite, and by the occurrence of Permian magmatic rocks like pegmatites (SCHUSTER & FRANK, 2000; THÖNI & MILLER, 2000), gabbros (MILLER & THÖNI, 1997), and granites (MORAUF, 1980).

The Wölz Complex is mainly formed by garnet-micaschist with intercalations of amphibolites and marbles. In some areas garnet porphyroblasts with optically and chemically distinct cores and younger rims occur. The cores are idiomorphic, almandine-rich and poor in grossular ($alm_{0.73}sps_{0.08}pyr_{0.09}grs_{0.09}$). They have a pinkish colour and contain inclusions of margarite ($ma_{0.83}pa_{0.13}ms_{0.04}$), paragonite ($pa_{0.92}ma_{0.06}ms_{0.02}$), muscovite ($ms_{0.91}pa_{0.09}ma_{0.00}$), epidote, quartz and ilmenite.

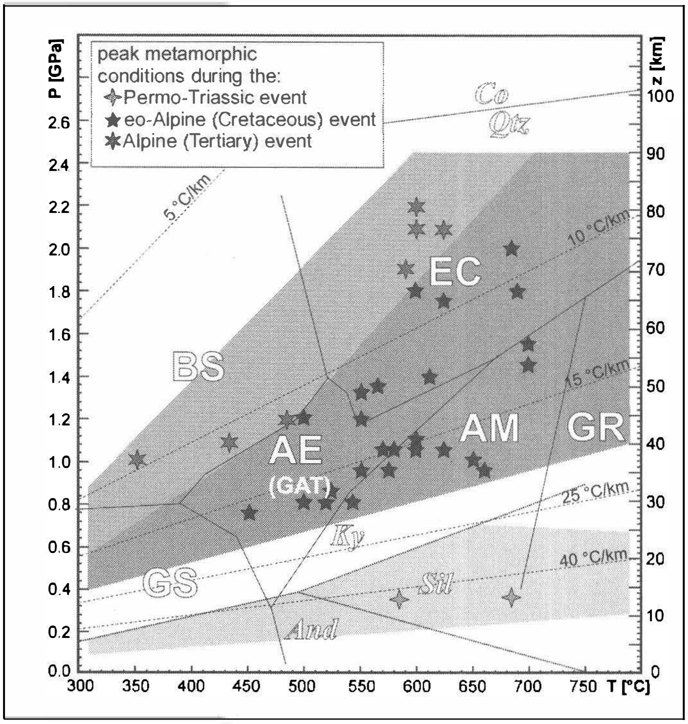

Fig. 3
Diagram showing the peak metamorphic P-T data referred in the text. The Permo-Triassic, Eo-Alpine and Alpine metamorphic event are characterised by different geothermal gradients during the metamorphic peak.

The core of one garnet yielded a well defined Sm-Nd crystallisation age of 269 ± 4 Ma and hence a Permian age of formation. Based on the coexistence of white mica phases during the growth of the garnet core, upper greenschist facies conditions at low pressures can be estimated (SCHUSTER & FRANK, 2000). Also from other units of the Wölz-Koralpe Nappe system garnet cores yielded Permian formation ages in the range of 265-285 Ma (THÖNI, 1999). They prove a metamorphic imprint of at least upper greenschist facies conditions for these areas.
In the Strallegg Complex the transformation of Permian andalusite and sillimanite-bearing assemblages into kyanite-bearing gneisses can be observed. This unit is composed of biotite-rich micaschists and migmatic gneisses, scarce amphibolites and intercalations of fine-gained granitic orthogneisses and pegmatites. Similar as in the Strieden Complex the andalusite and sillimanite-bearing lithologies contain relics of Variscan garnet and staurolite. They show mineral assemblages of Sil + And + Kfsp + Bt + Pl and also cordierite has been reported. Based on observations from TÖRÖK (1999) two sillimanite generations occur: the older developed by the breakdown of paragonitic mica by the reaction Pg + Qtz ⇔ Sil + Ab + H_2O. This sillimanite is present as inclusions within andalusite. The latter formed by the reaction St + Ms + Qtz ⇔ And + Bt + H_2O at lower pressures (Fig. 3). A younger sillimanite generation occurs within extensional shear bands and between boudinaged andalusite porphyroblasts. Metamorphic peak conditions reached 640-710 °C at 0.22- 0.38 GPa (DRAGANITS, 1998; TÖRÖK, 1999). The granites and pegmatites represent syn-metamorphic intrusions with respect to the HT/LP event. They are crosscutting the schistosity defined by the HT/LP assemblages, but they are also deformed by syn-metamorphic structures. The age of the HT/LP imprint is defined by Sm-Nd garnet isochrone ages of metasedimentary and magmatic rocks in the range of 263-286 Ma.

The Eo-Alpine transformation of the alumosilicate starts with the formation of distinct kyanite crystals along the edges and within cracks. Finally andalusite and sillimanite are totally replaced by fine-grained kyanite aggregates. These pseudomorphs are very typical even when they are affected by a strong deformation later on.

The Saualpe-Koralpe Complex consists of various kyanite-bearing micaschists and paragneisses with intercalated marbles, eclogites and amphibolites. Rocks of magmatic origin are (meta-)gabbros and frequent pegmatite gneisses. The present day metamorphic and structural behaviour is the result of the Eo-Alpine tectonothermal event, which reached eclogite and subsequent amphibolite facies conditions (see below). Relics of an amphibolite facies Permian HT/LP imprint are frequent kyanite pseudomorphs after andalusite and sillimanite, similar to those in the Strallegg Complex. Further Permian garnet cores and Permian pegmatites have been identified. The latter are interpreted as vein mobilisations from the host rocks (THÖNI & MILLER, 2000). Further gabbroic rocks yielded Permian crystallisation ages in the range of 240-285 Ma (MILLER & THÖNI, 1997; THÖNI, 1999). However, the most impressive relics of the HT/LP event are up to half a meter long kyanite pseudomorphs after chiastolithic andalusite from metapelites and idiomorphic kyanite pseudomorphs after andalusite within pre-existing andalusite-quartz veins. HABLER & THÖNI (2001) calculated metamorphic conditions of $590 \pm 20°C$ at 0.38 ± 0.1 GPa for the HT/LP imprint. They used relic assemblages preserved within garnet cores from metapelites. A summary of the Permian imprint in the Austroalpine unit was published by SCHUSTER et al. (2001).

2.3. Alpine metamorphic history

In the Eastern Alps Alpine tectonometamorphism is triggered by two independent plate tectonic events:

1) **The Eo-Alpine (Cretaceous) metamorphic event** is widespread within the Austroalpine unit. It is related to the continental collision following the closure of an embayment of the Tethys ocean. The latter opened in Triassic to Jurassic times in the southeast of the Austroalpine unit (STAMPFLI & MOSAR, 1999) and was closed in Upper Jurassic to Cretaceous times. The geometry during the closure of this embayment is not well understood yet. However, recent investigations argue that the northern part of the Austroalpine unit formed the tectonic lower plate, whereas the southern parts and the north-eastern margin of the Southalpine unit acted as the tectonic upper plate during the continental collision following the disapearance of the oceanic embayment (SCHMID et al., 2004). The peak of the Eo-Alpine metamorphic event was reached at about 100 Ma, the youngest cooling ages reach 65 Ma (FRANK et al. 1987a; THÖNI, 1999).
2) **The Tertiary Alpine metamorphic event** is due to the closure of the Jurassic to early Tertiary Briançonnais and Valais oceans (Alpine Tethys). According to WAGREICH (2001) the re-arrangement of the Penninic-Austroalpine border zone from a passive to an active continental margin began at about 120 Ma. From that time on the oceanic lithosphere and slices from the northern margin of the Austroalpine unit (Lower Austroalpine units) were subducted towards the south below (Upper) Austroalpine units. The Tertiary event reached blueschist facies conditions in some Mesozoic parts of Penninic windows and some units of the Lower Austroalpine (Tarntal nappe). Eclogite facies conditions occur only in a narrow zone of the Tauern Window.

After the thermal peak at about 30 Ma (BLANKENBURG et al., 1989) uplift and cooling is recorded by K-Ar and Ar-Ar ages on white micas and fission track ages on zircon and apatite (LUKSCHEITER & MORTEANI, 1980; GRUNDMANN & MORTEANI (1985); FÜGENSCHUH et al., 1998).

2.3.1. Eo-Alpine (Cretaceous) metamorphic event

In the Lower Austroalpine nappes the Eo-Alpine metamorphic imprint is expressed by a retrograde overprint on pre-Alpine metamorphic rock series and a prograde metamorphic imprint in Mesozoic cover sequences. During the retrogressive overprint the assemblage Chl + Ab + Ms + Qtz was stable in the basement rocks, indicating lower greenschist facies conditions. For the northern part of the Wechsel nappe MÜLLER et al. (1999) proposed temperatures of 350°C, whereas SLAPANSKY & FRANK (1987) estimated 350-400°C for the Radstadt nappe system.

In the Upper Austroalpine unit the Eo-Alpine metamorphic imprint shows a generally north-south orientated zonation, which is disrupted by Tertiary faults. Coming from the north the Eo-Alpine metamorphic conditions increase with structural depth from diagenetic up to greenschist facies conditions from the Northern Calcareous Alps down into the Silvretta-Seckau nappe system. Within the lower part of the overlying Wölz-Koralpe nappe system the metamorphic grade is increasing upwards from lower greenschist facies at the base to eclogite and high amphibolite facies in the central part. In the upper part it is decreasing upwards again to epidote-amphibolite or greenschist facies conditions at the top. The latter trend is continuing in the overlying Ötztal-Bundschuh and Drauzug-Gurktal nappe systems, where anchizonal or diagenetic conditions can be found in the tectonically uppermost units (Fig. 4). In the following chapter general outlines on this metamorphic zoning are given, whereas more detailed information on the metamorphic imprint of the individual units is given in HOINKES et al. (1999). Units, referred in here, are shown in a map by SCHUSTER et al. (2001, Fig. 1).

The metamorphic grades given for the Northern Calcareous Alps are based on illite-crystallinity data, coalification ranks and conodont alteration indices (CAI) (FERREIRO-MÄHLMANN, 1995; 1996; KRALIK & SCHRAMM, 1994; GAWLIK et al. 1994). Palygorskite occurs within unmetamorphosed sediments, whereas paragonite, margarite, pyrophyllite and paragonite/muscovite mixed layer minerals were formed during the Eo-Alpine thermal imprint (KRALIK et al., 1987). There is an overall southward increase of the metamorphic grade, with diagenetic conditions in the Bajuvaric and northern Tirolic nappe system, to upper anchizonal conditions and lowermost greenschist facies in the southern part of the Tirolic nappe system. This seems to be more complicated by local trends. For example, in the western part of the Northern Calcareous Alps lowermost greenschist faces is reported from the tectonic uppermost Krabachjoch Nappe (KÜRMANN, 1993) and on the other hand, along the southeastern margin of the Northern Calcareous Alps the conditions are decreasing upwards from upper anchizonal conditions within the Permoscythian metasediments of the Tirolic nappes to diagenetic conditions in the uppermost Schneeberg nappe (Juvavic Nappe system). GAWLICK et al. (1994) reported the distribution of conodont alteration indices (CAI) for large parts of the Northern Calcareous Alps. Based on this data also a Jurassic thermal event can be recognised. The highest indices up to CAI 7 can be found in the Juvavic nappe system (FRISCH & GAWLICK, 2003).

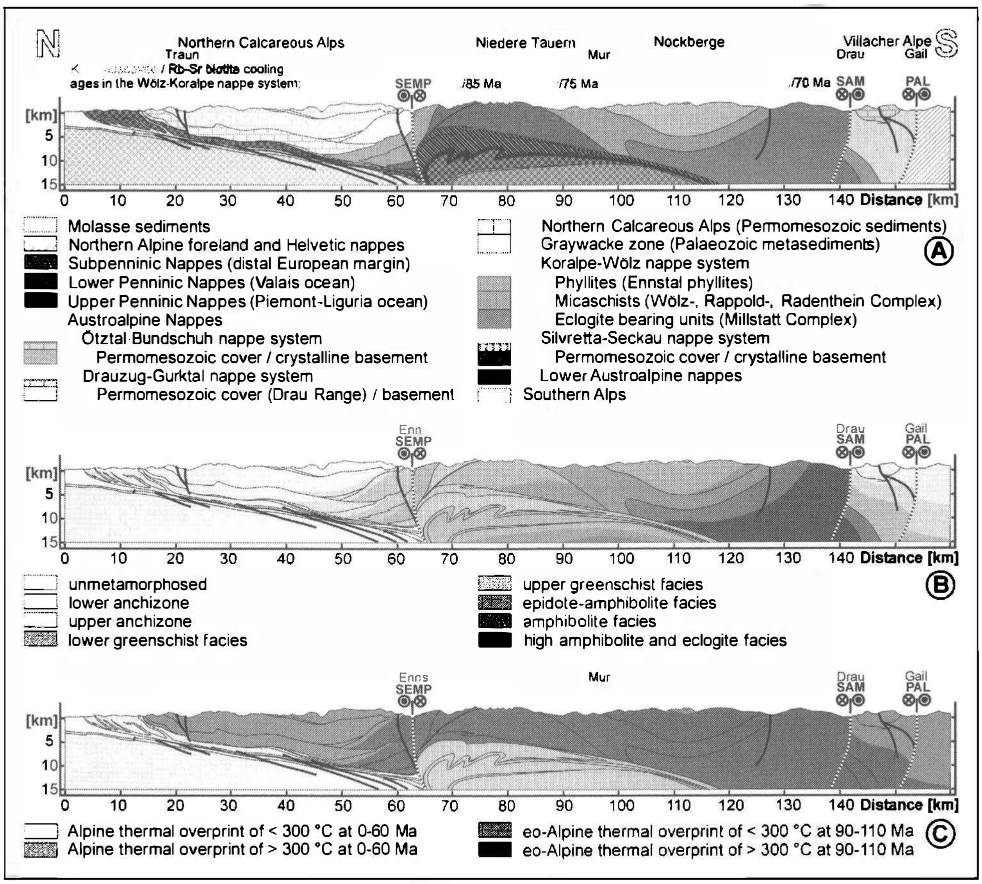

Fig. 4

Schematic transect through the eastern part of the Eastern Alps. The transects show the main tectonic units in (A), the metamorphic grade in (B) and the age distribution of the metamorphic imprint based on HANDY & OBERHÄNSLI (2004) in (C).

In the Noric, Silbersberg and Veitsch nappe of the Greywacke zone lower greenschist facies conditions are proved by illite crystallinity data, the grade of graphitisation and the occurrence of chloritoid. Only for some areas along the border to the Silvretta-Seckau nappe system temperatures of up to 500°C, indicating upper greenschist facies conditions, are reported. For these areas the local appearance of Eo-Alpine garnet is described by RATSCHBACHER & KLIMA (1985). In the Silvretta-Seckau nappe system high anchizonal to upper greenschist facies conditions have been reached along the northern margin. In the west, in the pre-Alpine amphibolite facies metamorphic rocks of the Silvretta Complex Variscan and Permo-Triassic K-Ar and Ar-Ar muscovite cooling ages are still preserved and even the Rb-Sr isotopic system in biotite is not totally reset. For this reason only anchizonal or lowermost greenschist facies conditions have been inferred as maximum conditions. On the other hand, in the Troiseck-Floning Komplex towards the east some biotite ages are totally reset and lower greenschist facies conditions are proved by the growth of Eo-Alpine biotite and chloritoid.

The highest conditions and an internal southward increase of the metamorphic grade are determined for the central part. In the north transgressive Permian metasediments on top of the Seckau Complex are characterised by the assemblage Ms + Ctd + Chl + Qtz, indicating upper greenschist facies conditions (500°C at 0.8 GPa). In this area Variscan Ar-Ar hornblende ages are still preserved. Towards the south epidote-amphibolite facies conditions of 550-600°C at 0.9-1.0 GPa and the total reset of the hornblende ages has been observed (FARYAD & HOINKES, 2001; 2003).
In the northern, tectonically lower part of the Wölz-Koralpe nappe system, the metamorphic grade is increasing upwards. Assemblages of Ms/Pg + Chl + Qtz ± Bt ± Grt ± Ep (Ennstal Phyllites) are typical for the northernmost part. The Wölz Complex above is characterised by prograde assemblages of predominantly micaschist (Grt ± St ± Ky ± Ab + Ms/Pg + Bt + Qtz ± Chl) with intercalations of amphibolites and marbles. An internal gradient is indicated by the distribution of staurolite and the local breakdown of staurolite by the reaction St + Qtz ⇔ Ky + Grt + H_2O. The amphibolites are variable and include massive amphibolites as well as mica-rich hornblende garben-schists (Ca-Amp + Grt + Ms/Pg + Pl + Chl ± Ep ± St ± Ky). Besides pure calcitic marbles also dolomitic marbles with assemblages of Cc + Dol + Qtz + Tr occur. According to FARYAD & HOINKES (2003) the metamorphic conditions in the uppermost parts of the unit reach 600-650°C at 1.0-1.1 GPa. From the same authors similar conditions have been reported for the overlying Rappold Complex. However the prograde breakdown of staurolite is very typical in the latter unit. For the Grobgneiss Complex in the eastern part of the Eastern Alps Eo-Alpine metamorphic upper greenschist facies and epidote amphibolite facies conditions of 550°C at 0.9 GPa have been determined (KOLLER et al., 2004). Somewhat higher conditions of ~560°C at 1.3 GPa were reported for the overlying Strallegg Complex (DRAGANITS, 1998; TÖRÖK 1999).
The central part of the Wölz-Koralpe nappe system is characterised by eclogite-bearing (Grt + Omp + Ca-Amp + Ep/Zoi +Ru + Qtz + Phe) units. Peak conditions for the easternmost Sieggraben Complex are 710°C at 1.5 GPa (NEUBAUER et al., 1999b; PUTIS et al., 2000). Variable results are reported for the Saualpe-Koralpe Complex (600°C at 1.8 GPa. (MILLER, 1990); 685°C at 2.0 GPa (MILLER & THÖNI, 1997); 700°C at 1.8 GPa (STÜWE & POWELL, 1995); 700°C at 1.6 GPa (GREGUREK et al., 1997); 690°C at 1.8 GPa (FARYAD & HOINKES, 2003). These widespread results may be due to the fact that the Saualpe-Koralpe complex consists of several subunits which might have reached different depths during the Eo-Alpine collisional event. Towards the west, conditions of c. 600°C at 1.1 GPa have been determined for the Millstatt and Polinik Complexes (HOINKES et al., 1999) whereas 550°C at 1.2 GPa were measured for the westernmost occurrence in the Texel mountains (HOINKES et al., 1991). All the eclogite-bearing units show a subsequent overprint at (high-)amphibolite facies conditions.
Decreasing metamorphic conditions are characteristic in the upper part of the Wölz-Koralpe nappe system: On top of the Saualpe-Koralpe Complex the metamorphic grade is decreasing from amphibolite facies conditions of 570°C at 1.05 GPa within the garnet-micaschists (Grt + Ky+ St ± Ctd + Ms/Pg + Qtz+ ± Chl) of the Plankogel Complex (GREGUREK et al., 1997) to greenschist facies conditions in the micaschists above. Towards the west investigations yielded 600°C at 1.1 GPa for the Radenthein Complex (KOROKNAI et al., 1999) and 580°C at 1.05 GPa for the Schneeberg Complex (KONZETT & HOINKES, 1996), which are composed of lithologies very similar to those of the Wölz Complex.
In general the P-T-t paths in the lower part of the Wölz-Koralpe nappe system show a pronounced heating after the metamorphic peak, whereas those from the central and upper part are characterised by isothermal decompression.

In the Ötztal-Bundschuh and Gurktal-Drauzug nappe systems the upward decrease in the metamorphic grade is continuing. In the west the metamorphic grade is decresing from epidote-amphibolite facies conditions along the southeastern margin of the Ötztal Complex to anchizonal conditions in the northwest. The same trend is visible in the transgressive Mesozoic cover. The epidote amphibolite facies is indicated by the occurrence of an Eo-Alpine garnet. Towards the north the occurrence of chloritoid defines the area of upper greenschist facies conditions. Further to the north the formation of stilpnomelane and a second generation of phengitic white mica within metagranitoides indicates a LT/HP imprint (< 300°C at c. 0.5 GPa). In the overlying Steinach Nappe high anchizonal conditions can be expected by coalification ranks.
The Bundschuh Complex is very similar to the Ötztal Complex. In its tectonic lowermost part amphibolite facies conditions of 600°C at 1.05 GPa were determined by KOROKNAI et al. (1999), whereas the conditions are decreasing to (lower)-greenschist facies conditions below and in the transgressive Mesozoic cover (SCHUSTER & FRANK, 2000). Assemblages of Ms + Chl ± Grt + Ab + Bt + Ep + Czoi + Cc + Dol suggest upper greenschist facies conditions in the Paleozoic sequences of the overlying Murau nappe. The pre-Alpine medium grade rocks of the Ackerl nappe and the Paleozoic metasediments of the uppermost Stolzalpen nappe show lower greenschist facies and anchizonal conditions. According to the fact that the latter unit experienced a similar metamorphic grade during the Variscan event, the detailed distribution of the Eo-Alpine anchizonal and lower greenschist facies imprint is not known (HOINKES et al., 1999). The late Carboniferous cover sequences of the Stolzalpen nappe show an anchizonal imprint, indicated by pyrophyllite, paragonite/muscovite mixed layer minerals and paragonite (SCHRAMM, 1982).
Within the Austroalpine units to the south of the SAM (HOINKES et al. 1999) (Fig. 1) the metamorphic grade is decreasing upwards. Greenschist facies conditions have been reached only in the northern part of the Goldeck mountains, whereas anchizonal conditions can be expected for the main part of the crystalline basement. This is mostly based on Rb-Sr biotite ages, which yield Eo-Alpine ages in the northern Goldeck mountains (DEUTSCH, 1988) and partial reset or unaffected pre-Alpine ages in the other areas. Based on illite-cristallinity and vitrinite reflection data anchizonal or diagentic conditions occur within the Mesozoic cover sequences of the Drau Range (RANTITSCH, 2001; RANTITSCH & RAINER, 2003)

The observed Eo-alpine metamorphic zoning of the Austroalpine unit can be explained as follows: Based on a number of geochronological data (THÖNI, 1999) the pressure peak occurred at 100 ± 10 Ma. These data include Ar-Ar ages on fine fractions of white mica and whole rocks of low grade metamorphic rocks from tectonically high levels, as well as Sm-Nd garnet isochron ages on high-pressure rocks. Prior to 100 Ma shortening within the Austroalpine realm was compensated by W-NW directed (RATSCHBACHER, 1986) thrusting in the brittle tectonic wedge of the upper part and ductile deformation in the lower part of the crust. The northern part of the Austroalpine nappe stack, including the Northern Calcareous Alps, the Greywacke zone and the northern part of the Silvretta-Seckau nappe system, as well as the southern part of the Austroalpine unit comprising the Ötztal-Bundschuh and Gurktal-Drauzug nappe systems were substantially formed by this event. During the metamorphic peak their principal present day relations within the Austroalpine nappe stack were established. For this reason this units exhibit an upright metamorphic zoning.

After 100 Ma the deeply buried, highly metamorphosed and partly eclogite-bearing nappes of the Wölz-Koralpe nappe system were exhumed. In the area to the east of the Tauern Window their exhumation is due to NW-N directed thrusting (e.g. KROHE, 1987) in the lower part and by SE-directed normal faulting in the upper part of the nappe system. This post-peak metamorphic tectonic caused the inversion of the peak metamorphic grade in the lower part of the Wölz-Koralpe nappe system (Fig. 5). Therefor the Wölz-Koralpe nappe system has been defined as an extruding metamorphic wedge by SCHMID et al. (2004). Towards the west the eclogite-bearing units are outcropping in a back folding structure of the wedge. As only the upper limb of the back fold structure is visible, an upright metamorphic zoning can be observed in the field (Fig. 4).
In general, the metamorphic cooling ages of the Eo-Alpine metamorphic event show an interference of two trends. Firstly, within the nappe piles formed prior to the metamorphic peak the oldest Eo-Alpine cooling ages are younger than the metamorphic peak (< 110 Ma) and decrease downward in the section. The second trend shows younger ages towards the south within the units of the metamorphic wedge (Wölz-Koralpe nappe system). In the northern, lower part of the wedge Ar-Ar muscovite ages and Rb-Sr biotite ages are c. 90 Ma and 85 Ma respectively. In the southern part and also in the back fold structure cooling ages of ~75 Ma (Ar-Ar muscovite) and ~70 Ma (Rb-Sr biotite ages) have been measured (Fig. 4A).

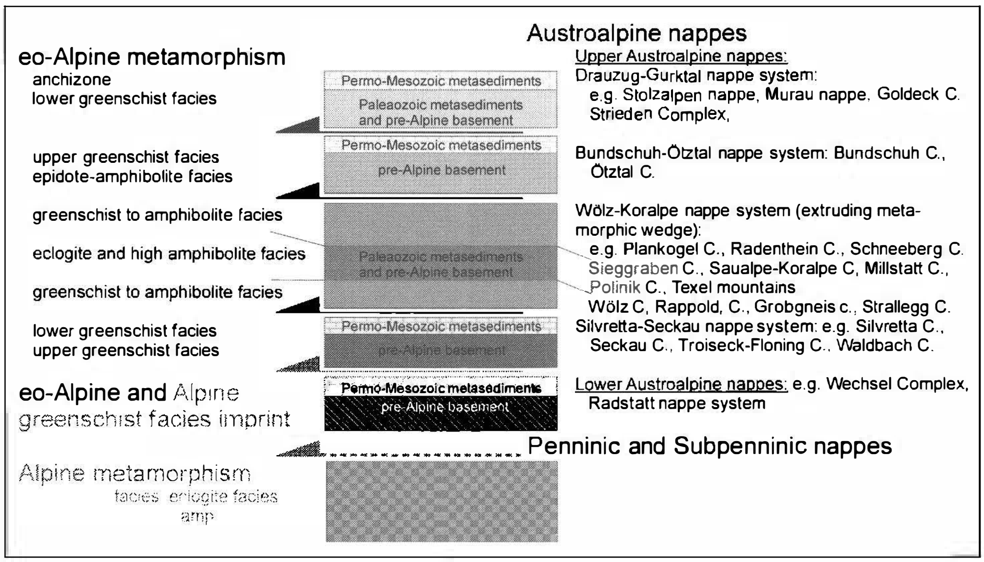

Fig. 5

Schematic nappe stack of the SE part of the Eastern Alps with the metamorphic evolution. Further the posible correlation to individual Austroalpine nappes from the western part of the Eastern Alps are show together with their metamorphic evolution.

2.3.2. The Tertiary Alpine metamorphic event

The Tertiary metamorphism is restricted to the Penninic Zone including the Suppenninic nappes and its immediate neighboring units, i.e. parts of the Lower Austroalpine unit (DINGELDEY et al., 1997, LIU et al., 2001) and the Austroalpine units just southwest of the Tauern Window (BORSI et al., 1978).

The Penninic nappes, widely distributed in the Western and Central Alps, can be followed along a series of windows across the whole range of the Eastern Alps. These are, from the W to the E the Lower Engadin Window (LEW), the Tauern Window (TW) and a group of small windows at the eastern margin of the Alps called the Rechnitz Window Group (RWG) (HÖCK & KOLLER, 1989; KOLLER & HÖCK, 1990). The Rhenodanubian Flyschzone is also ascribed to the Penninic realm (e.g. OBERHAUSER, 1995).
Stratigraphically, the metamorphics in the Penninic zone range form the Late Proterozoic(?) to the Paleogene. Pre-Mesozoic rocks are restricted to the TW and to small fragments at the basement of the Tasna nappe in the LEW (FLORINETH & FROITZHEIM, 1994). Mesozoic rocks, such as Triassic quartzites, marbles and dolomites as well as Jurassic and Cretaceous phyllites, micaschists, calcareous micaschists and other metasediments, ophiolites and non-ophiolitic volcanics occur throughout all Penninic windows. The upper stratigraphic boundary of the Mesozoic to Cenozoic sequences is still under discussion. Late Cretaceous and Paleogene sediments are proven from the LEW (OBERHAUSER, 1995), Early Cretaceous from the TW (REITZ et al., 1990) and the RWG (PAHR, 1980). The occurrence of Late Cretaceous and Tertiary sediments in the more easterly windows is questionable.
The Radstadt nappe system in the northeast of the Tauern Window is built up by slices of pre-Alpine amphibolite facies rocks and Mesozoic cover sequences. An Alpine lower greenschist metamorphic imprint is indicated by prograde assemblages in the Mesozoic rocks and retrogression within the basement.

2.3.2.1 Lower Engadine Window

Situated between the Eastern and Central Alps, the Lower Engadine Window forms an antiform trending NE-SW (KLÄY, 1957). It exposes a stack of Penninic nappes, overlain and framed by Austroalpine nappes. The Lower Engadine Window can be subdivided into several distinct units (CADISCH et al., 1968; TRÜMPY, 1975; OBERHAUSER, 1980); from top to base they are as follows.
The **Arosa zone** is a highly tectonized ophiolite-bearing unit (RING et al., 1990) with an ophiolite sequence mostly of serpentinites, gabbros and basalts (HÖCK & KOLLER, 1987) of the Piemont-Ligurian ocean. It is coverd by a sequence of radiolarian cherts, pelagic limestones, black shales of Hauterivian-Aptian age (WEISSERT & BERNOULLI, 1985) and flysch. The Arosa zone in the eastern part of the Grisons continues southward into the Platta nappe with similar chemical and paleogeographic features (DIETRICH, 1976; FRISCH et al., 1994). It is likely to be correlative with the Matrei zone in the Tauern Window (FRISCH et al., 1987) that was interpreted as part of an imbricated thrust stack formed by the overriding of the Austroalpine units. According to Ring (1992) the Matrei zone can be compared to an accretionary prism.
The metamorphism of the ophiolites is twofold; an older HT oceanic metamorphism can be separated from a younger HP metamorphism. Evidence for the former comes from the replacement of gabbroic clinopyroxenes by amphiboles (pargasite, magnesio hornblende to actinolite) formed at relatively high temperatures. This together with some metasomatic changes of the bulk geochemistry (mainly Na enrichment) and some local strong oxidation argues for this hydrothermal event. Remnants of the E-W striking oceanic high temperature deformation planes in the gabbros show commonly formation of black amphibole in their vicinity indication of H_2O infiltration. The cores of these amphiboles in the altered gabbros contain still high Cl contents up to 4000 ppm.

In the hyaloclastites and pillow breccias the hydrothermal influence of the oceanic metamorphism causes locally ~E-W striking epidote-rich veins. The same event causes locally an intensive oxidation, defined by the dark red color of some hyaloclastite layers.
The Tertiary Alpine metamorphic grade of the Idalp ophiolite sequence belongs to the LT conditions at the transition between greenschist and blueschist facies with 0.7-0.9 GPa at~350°C. The mineral assemblages are defined by pumpellyite + chlorite + albite. The pumpellyite of the metagabbro is Mg-rich, the green pumpellyite of the diabases with a $Fe_{tot}/(Fe_{tot}+Al)$ range between 0.11-0.15. Prograde replacement to epidote is rare. In the metabasite locally a high phengitic micas with an Si of 3.6 pfu were found.
The **Tasna nappe** is a continuous sedimentary sequence from the Permo-Triassic to the late Cretaceous, locally associated with slices of continental basement (WAIBEL & FRISCH, 1989). The Lias-Cretaceous sequence is composed mainly of turbidites with associated debris flows and pelagic limestones. However, recent studies in the Tasna nappe basement (FLORINETH & FROITZHEIM, 1994) revealed a preserved transition from the continental crust of the Briançonnais terrane to the oceanic crust of the Valais ocean. The metamorphic conditions belong to the lower greenschist facies.
The **Ramosch Zone** represents the transition between a continental unit (Briançonnais) and an oceanic (Valais) unit (FLORINETH & FROITZHEIM, 1994). The main unit is of a serpentinized peridotite-body associated with ophicarbonates and serpentinite breccias (VUICHARD, 1984). Metagabbros are lenticular within and adjacent to the serpentinite body. Directly underlying the serpentinite along an Alpine, top-north directed thrust fault, pillow basalts represent a part of the Valais ocean (FROITZHEIM et al., 1996). Further a huge mass of Bündnerschiefer, forming the deepest units of the Lower Engadine Window, with up to 10 km of calcschists interbedded with shales and quartzites (HITZ, 1995). It grades upward into flysch deposits that are lithologically very similar to the Bündnerschiefer and are dated as Late Cretaceous to Eocene (ZIEGLER, 1956). Some mafic bodies are intercalated within the schists particularly in the core of the window. These bodies are mainly composed of pillow basalts and hyaloclastites associated with metaradiolarites, where geochemical criteria suggest an oceanic basement (DÜRR et al., 1993). This unit is the remnant of the northern Penninic ocean, the Valais basin (FRISCH, 1976; TRÜMPY, 1980; STAMPFLI, 1993).

In Bündnerschiefer and associated metabasites of the LEW two units displaying distinct metamorphic have been reported by BOUSQUET et al. (1998, 2002). The structurally lower unit (Mundin unit) has a clear HP-LT history, whereas in the upper unit (Arina unit) no obvious HP-LT mineral assemblages were found.
In the Mundin unit blueschist metamorphic conditions are exclusively found in the central part of the window forming the core of a late anticline. These conditions are characterized by the occurrences of (Fe,Mg)-carpholite in metasediments (GOFFÉ & OBERHÄNSLI, 1992; OBERHÄNSLI et al., 1995). In the core of the Mundin unit antiform, carpholite appears as relicts. For the Mundin unit, P-T estimates range between 1.1-1.3 GPa for a temperature around 350-375°C (BOUSQUET et al., 2002). Indication of the LT-HP metamorphic assemblages in the metabasites are rare and occur mainly in samples which unterwent prior an oceanic metamorphism. Glaucophane (BOUSQUET et al., 1998) and Na-pyroxene were found in metabasites. The Na-pyroxene assemblages are partly replaced by riebeckite or Mg-riebeckite. Also aragonite was found as a relict in the Na-pyroxene bearing assemblages, partly or strongly replaced by calcite.

In the Arina unit, evidence for HP metamorphism is scarce. However, crossite and lawsonite occur in metabasites (LEIMSER & PURTSCHELLER, 1980), and Mg-pumpellyite in association with chlorite, albite, and phengite occur in metapelites. The P-T conditions calculated by BOUSQUET et al. (1998) range around 0.6 GPa, 300°C.

2.3.2.2. Tauern Window

The oldest rocks in the TW are found in a volcano-sedimentary sequence comprising ophiolites, island arc volcanics and associated sediments of Late Proterozoic to Paleozoic age (Habach Group). A part of this sequence underwent pre-Mesozoic metamorphism, partly migmatisation and was intruded by Variscan granitoids. According to the tectonic classification of SCHMID et al. (2004) the Paleozoic sequences belong to the Subpenninic nappes.
The post-Variscan sequences start with Permo-Triassic quartzites, middle Triassic limestones and dolomites and upper Triassic sandstones and shales. The Triassic rocks are overlain by shales, marls and shaly limestones of Jurassic to Early Cretaceous age (Bündnerschiefer Group). Locally, sandstones, breccias and arcoses occur. Associated with the sediments are ophiolites and other basic intrusions and volcanics. The youngest sediments proven so far are of Early Cretaceous age. Comparison with lithologically similar sediments in the LEW and the Penninic realm in the Western Alps suggests the occurrence of younger sediments.

Tectonically two nappes are generally delineated (FRISCH, 1976): the lower Venediger nappe (Subpenninic nappes according to SCHMID et al. (2004)) comprising most of the pre-Mesozoic rocks and relatively little Mesozoic sediments and volcanics and the higher Glockner nappe (Lower Penninic nappes according to SCHMID et al. (2004) including most of the Triassic rocks, the Bündnerschiefer and the ophiolites. Both nappes were later folded forming a huge anticline with an axis following approximately the main ridge of the Alps. Apart from the pre-Mesozoic metamorphism three episodes of metamorphic events were recognized: an eclogite event, a blueschist metamorphism, and the final greenschist to amphibolite facies metamorphism. The eclogitisation affects only a relatively small strip mainly at the southern escarpment of the TW, the blueschist metamorphism is mo widely distributed but restricted to the ophiolites, their immediate cover and the areas tectonically below. The Tertiary greenschist to amphibolite facies metamorphism can be seen in all rocks of the TW.
Two metamorphic events are recognizable in all Penninic windows where the older is regarded as a HP/LT metamorphism and the younger as Barrovian type. Only in the TW an earlier eclogite metamorphism is recorded with a retrograde evolution path, entirely different from the rest of the Penninic metamorphics of the Eastern Alps.
The most conspicuous eclogite assemblages are found in metabasic rocks but some original basalt - sediment interfaces are still preserved. Consequently some metasediments exhibit high-pressure mineral assemblages (FRANK et al., 1987b; FRANZ & SPEAR, 1983). Inclusions in the eclogitic mineral assemblage in the metabasites indicate a greenschist to amphibolite facies event prior to the eclogitisation (MILLER, 1977; DACHS, 1986; DACHS et al., 1991).
The P-T conditions of the formation of eclogite are fairly well established within the analytical error and the errors of the different geobarometers used. The eclogitized metabasics and metasediments passed through a mantle/crust segment in a depth of 70 km (possibly 85 km according to STÖCKHERT et al., 1997). With T_{max} around 600- 630°C and P ~1.9-2.2 GPa (HOSCHEK, 2001) they formed at a very low geothermal gradient of 7-9°C/km, typical for subduction zones.

It should be noted here that only the structurally lowest part of the Mesozoic sediments and volcanics below the ophiolites underwent the eclogite metamorphism.
Whereas the P-T conditions are well constraint no dating of the eclogites is available yet. If the Ar-Ar age data of ZIMMERMANN et al. (1994) are valid for the blueschist event, the eclogites formed prior to the Eocene/Oligocene boundary. ZIMMERMANN et al. (1994) estimate the age of mica formation related to the eclogites between 40 and 50 Ma.
By contrast to the eclogite assemblages, which are well preserved, the minerals formed during the blueschist event survived only rarely. They can be traced by some individual mineral relicts and by pseudomorphs. The most conspicuous relics from this stage are pseudomorphs after lawsonite. Some jadeite poor omphacites coexisting with albite rich plagicolase derived from the decompositon of a more jadeite rich omphacite also represents the blueschist facies. Occasionally blue amphiboles such as glaucophane and/or crossite are preserved and probably barroisitic amphiboles. Associated with this stage and possibly also with the eclogite event are high Si phengite with Si = 3.30-3.40 pfu. In extreme cases the Si content may reach 3.65 pfu (ZIMMERMANN et al., 1994). From that data FRANK et al. (1987a) estimated the conditions of blueschist formation as T = 400-450°C and P around 0.9 GPa. ZIMMERMANN et al. (1994) calculated 1.0 GPa at 400°C. The blueschist event is neither well constraint in respect to the P–T path, nor in respect to age dating. The data by ZIMMERMANN et al. (1994) suggest for the TW an age of late Eocene - early Oligocene for the formation of the blueschist assemblages. Again the low thermal gradient of 10-13°C/km suggests a subduction related environment.
At the southern rim of the TW the zone of Matrei (Upper Penninic nappes according to SCHMID et al., 2004) consists of various lithologies including serpentinites and metabasites. Below the serpentinites thin horizons of blueschist assemblages in basaltic to ophicarbonate lithologies were found recently in several localities (KOLLER & PESTAL, 2003). This assemblage contains blue amphiboles or an older alkali pyroxene (up to 20% Jd), and stilpnomelane together with albite. In some cases a replacement to bluisch-green amphiboles is common.

2.3.2.3. Rechnitz Window Group

At the eastern end of the Alps close to the Austrian-Hungarian border several small Penninic windows occur below the Lower Austroalpine nappes. All these windows comprise huge masses of Mesozoic metasediments and locally some ophiolites. The lithology consists of a several km thick sequence of metasediments with calcareous micaschists, quartz-phyllites, graphite phyllites, rare breccias and few horizons of rauhwackes. Within the ophiolitic section remnants of oceanic metamorphism occur together with various degrees of oxidation. This event can be traced in most of the metagabbros and ophicarbonates, as well as in some metabasalts (KOLLER, 1985).

Blueschist facies event

Within the ophiolitic sequence remnants of a HP/LT event are widespread. Typical minerals are alkali pyroxenes, glaucophane or crossit, rare pseudomorphs of lawsonite, high-Si phengite, Mg-rich pumpellyite, stilpnomelane, hematite and rutile. At high Fe^{3+} contents in metabasites alkali pyroxene+hematite and rutile occur. No clear high pressure assemblage can be defined for the metabasalts containing only rare relics of blue amphibole, stilnomelane and pseudomorphs after lawsonite. High-Si phengite is also observable in metabasaltes and common in metasediments. For the blueschist facies event KOLLER (1985) calculated temperatures of 330-370°C at a minimum pressure of 0.6-0.8 GPa.

Low-pressure greenschist event
The high-pressure event is followed by a common greenschist overprint forming the general assemblages (metabasalts, metasedimentes). From the north to the south, there is a slight increase in temperature observable, which can be defined by following mineral isogrades: (1) Disappearance of metastable stilpnomelane and Mg-pumpelleyite in the northern part of the Rechnitz Window, (2) first appearance of green biotite in the northern part of the Bernstein Window, and (3) the first appearance of garnet in metapelites is restricted to the southernmost outcrops of the Penninic units.
No reliable age dating exists from the high pressure event. The greenschist event is dated by K-Ar ages of muscovite in the range of 22-19 Ma (FRANK in KOLLER, 1985). Fission-track ages were reported by DUNKL & DEMÉNY (1997) for zircon from 21.9-13.4 Ma and for apatite from 7.3-9.7 Ma. Furthermore the Penninic rocks of the RWG are overlain by non-metamorphosed sediments of Miocene and Pliocene age (PAHR, 1980).

2.3.2.4. Lower Austroalpine

2.3.2.4.1. Radstadt nappe system
The Lower Austroalpine nappes of the "Radstädter Tauern" form the NE rim of the Tauern Window (TOLLMANN, 1977; HÄUSLER, 1987). They contain the tectonically highest quartz-phyllite nappes with an inverse layering and different Permo-Mesozoic sequences, as the Hochfeind, Lantschfeld, Pleisling and Kesselspitz nappes. Well defined modern P-T path investigations on the Alpidic metamorphic evolution are still missing.
In the basement the Alpidic metamorphic event defines a retrograde evolution. The first geochronological results obtained by SLAPANSKY & FRANK (1987) on white micas (K-Ar and Ar-Ar ages) revealed a decreasing age from the uppermost nappe (~100 Ma) to the base (~50 Ma). More recent studies by LIU et al. (2001) confirm the general trend, giving Cretaceous ages in the upper Radstadt nappes and Paleogene age in the lower Hochfeind nappe. Similar ages were obtained by DINGELDEY et al. (1997) from the Reckner nappe.
The metamorphic evolution of the Permo-Mesozoic sediment sequences can be defined by the assemblage of phengite + chlorite and without forming biotite. Only locally also chloritoid and kyanite were mentioned by VOLL (1977). Temperatures of 450°C and pressures of at least 0.3 GPa have been assumed by SLAPANSKY & FRANK (1987). In general there is an increase of metamorphic conditions towards to the south.

2.3.2.4.2. Tarntal Nappes
The Lower Austroalpine Nappes cover the Penninic rocks of the TW also at the NW (Tarntal mountains). According to TOLLMANN (1977) the tectonic succession consists in the NW of the Tauern Window of three individual nappes. From the base to the top they are the Innsbruck quartzphyllite nappe, the Hippold nappe and the Reckner nappe.
The Innsbruck quartzphyllite nappe consists of various phyllites with rare diabases and quartz-porphyries, further carbonate (calcite, dolomite and magnesite) lenses. The top of this sequence is formed by Permo-Triassic sediments. By contrast, the Hippold and Reckner nappe are built up by a huge variety of partly fossil bearing Mesozoic sediment sequences ranging from Skyth to Malm ages (ENZENBERG, 1967; ENZENBERG-PRAEHAUSER, 1976). The top of the Reckner nappe is formed by the serpentinites and blueschists of the Reckner complex (DINGELDEY et al., 1997).

For both, the Reckner and the Hippold nappe a Tertiary HP/LT event in the range of ~350°C and ~1.0 GPa has been reported by DINGELDEY et al. (1997). Typical minerals of this event are alkalipyroxenes, Mg-rich pumpellyite, stilpnomelane and high Si phengite. The Penninic metasediments adjoining the Hippold nappe exhibit only intermediate pressure conditions (0.6-0.7 GPa).
This high pressure event was followed by a classical greenschist paragenesis with blue amphiboles replacing the alkalipyroxenes, low-Si muscovites, epidote, green biotite instead of stilpnomelane. Only a LP/LT event was found in the underlying Innsbruck Quartzphyllite nappe (~400 °C and < 0.4 GPa).
Ar-Ar-measurements on high-Si phengites from the Reckner nappe recorded ages around 50 Ma. In the underlying Hippold nappe and in the adjoining Penninic "Bünderschiefer" the high-Si phengites define ages between 44-37 Ma (DINGELDEY et al., 1997). Only rejuvenisation of Variscan micas and no clear Alpidic $^{40}Ar/^{39}Ar$ plateau ages were found in the Innsbruck Quartzphyllite nappe.

2.3.2.4. Correlation of the Penninic Windows of the Eastern Alps

The subsequent greenschist to amphibolite facies event has its lowest Tmax with 350°C in the LEW. In the RWG a T_{max} of 450°C is recorded and in the TW between 500-550°C. T_{max} is combined with a pressure of 0.2-0.4 GPa in the LEW, 0.3-0.4 GPa in the RWG and 0.6-0.8 GPa, locally reaching up to 1.0 GPa in the TW approaching a geothermal gradient of 20-35°C/km, typical for a Barrovian type metamorphism. It is coeval with the total disappearance of the Penninic zone beneath the Austro-Alpine nappes. This metamorphic stage was reached shortly after 30 Ma and is further recorded by cooling ages down to 16 Ma. Similar cooling ages are reported from the RGW, the scarce data from the LEW record probably the onset of the low grade metamorphism. The cooling and exhumation in the TW and RWG can be followed through fission track studies of apatites down to 4 and 7 Ma respectively (FÜGENSCHUH et al., 1998).

3. Conclusions

The distribution of the metamorphic facies zones in the Eastern Alps is mainly controlled by the northwards transport of the Austroalpine nappes. They show a Cretaceous metamorphism and are thrusted over the Penninic domains with Tertiary metamorphism (Fig. 4). The latter are exposed in the Eastern Alps only as tectonic windows.

The ***Eo-Alpine (Cretaceous) metamorphic event*** is widespread within and restricted to the Austroalpine unit. It is related to the continental collision following the closure of an embayment of the Tethys ocean during late Jurassic to Cretaceous times. Recent investigations indicate that the northern part of the Austroalpine unit forms the tectonic lower plate. The southern parts and the north-eastern margin of the Southalpine unit acted as the tectonic upper plate during the continental collision following the disappearance of the oceanic embayment (SCHMID et al., 2004). In the Austroalpine nappes the Eo-Alpine metamorphic event overprints Variscan and/or Permo-Triassic metamorphic rocks as well as Permo-Mesozoic sedimentary sequences. The peak of the Eo-Alpine metamorphic event was reached at about 100 Ma, the youngest cooling ages are recorded at 65 Ma (THÖNI, 1999).

The metamorphic conditions reached sub-greenschist and greenschist facies in the northern part of the Austroalpine. To the south, in the Wölz-Koralpe nappe system the conditions increase upwards up to eclogite facies in the middle part of the nappe system (Fig. 5). In its upper part of the Wölz-Koralpe nappe system and in the overlying units the metamorphic degree is decreasing again until sub-greenschist facies.This zoning indicates a transported metamorphism at least in the Wölz-Koralpe nappe system.

The ***Tertiary Alpine metamorphic event*** is due to the closure of the Jurassic to early Tertiary Briançonnais and Valais oceans (Alpine Tethys). According to WAGREICH (2001) the re-arrangement of the Penninic-Austroalpine border zone from a passive to an active continental margin starts at about 120 Ma. From that time on the oceanic lithosphere and slices from the northern margin of the Austroalpine unit (Lower Austroalpine units) were subducted towards the south below (Upper) Austroalpine units. The Tertiary event reaches blueschist facies conditions in some Mesozoic parts of Penninic windows and some units of the Lower Austro-alpine (Tarntal nappe). Eclogite facies conditions followed by a blueschist event occur only in a narrow zone of the Tauern Window. The thermal peak ranges from greenschist to amphibolite facies, the latter was only reached in the central part of the Tauern Window. After the thermal peak at about 30 Ma (BLANKENBURG et al., 1989) uplift and cooling is recorded by K-Ar and Ar-Ar ages on white micas and fission track ages on zircon and apatite (LUKSCHEITER & MORTEANI, 1980; GRUNDMANN, & MORTEANI, (1985); FÜGENSCHUH et al., 1998). In the lower nappes of the Lower Austroalpine units the Tertiary Alpine metamorphism over-prints the Cretaceous metamorphic event.

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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.

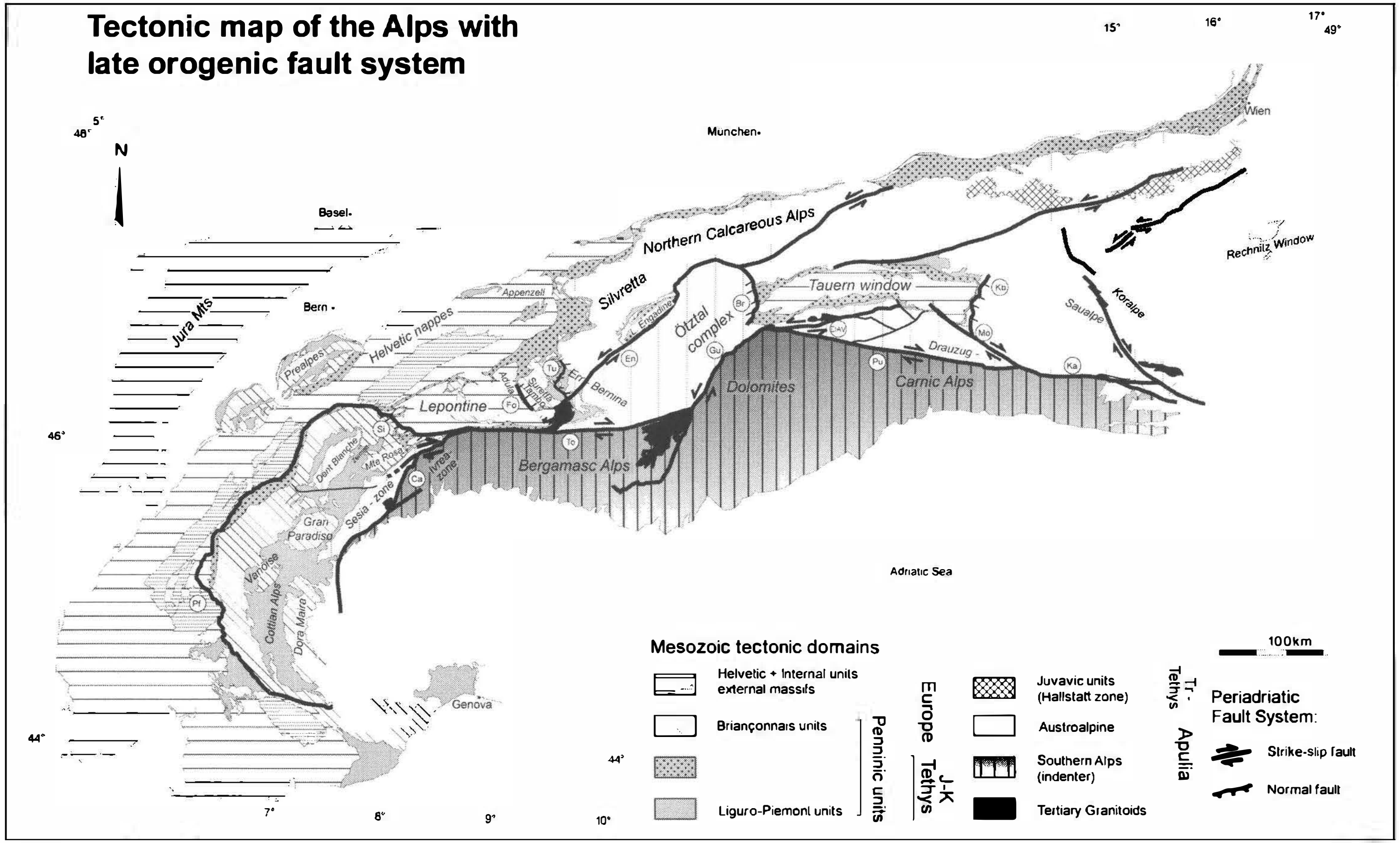

Figure 1

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.

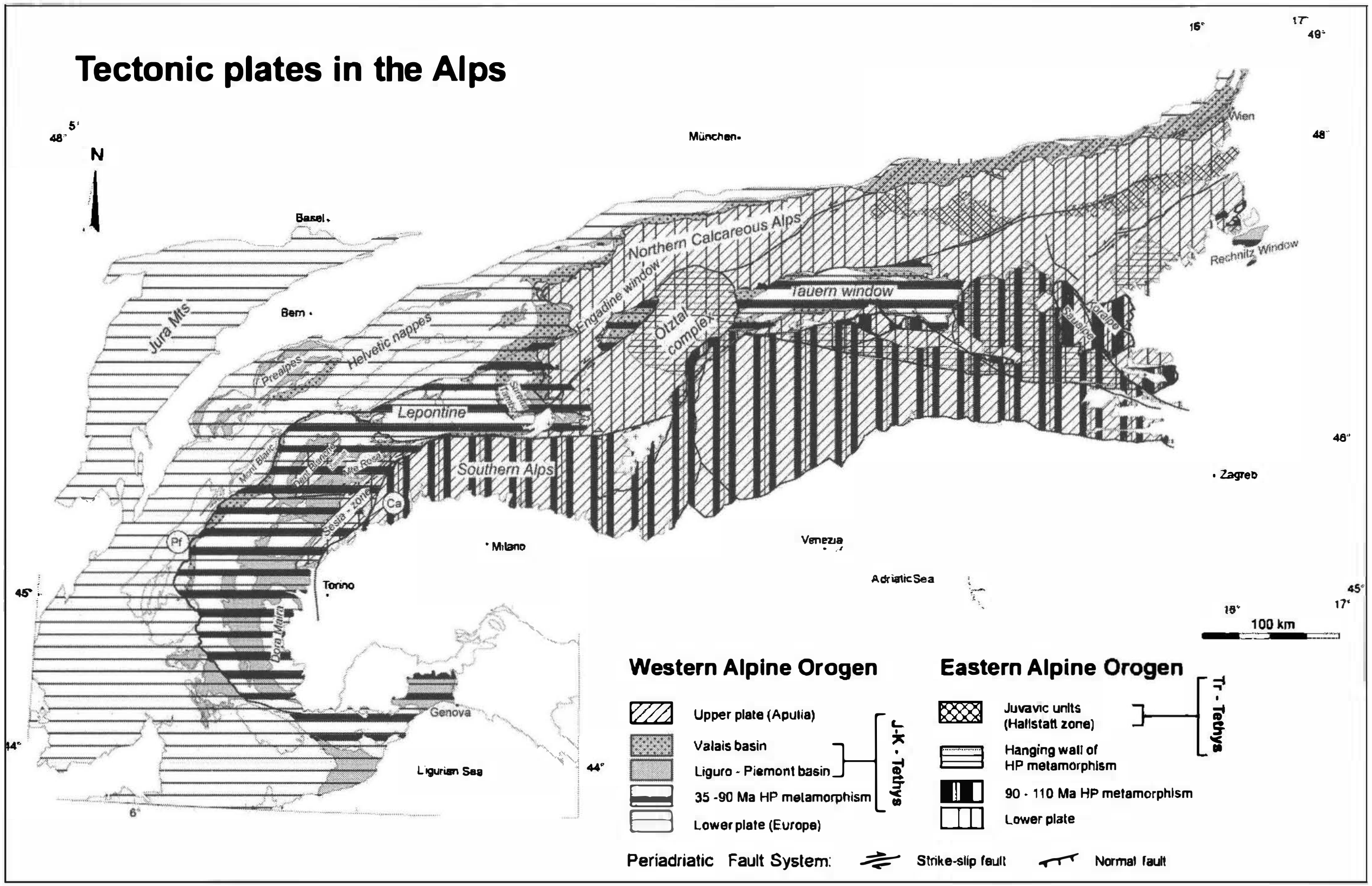

Figure 2

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 intra-granular 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 hanging-wall 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 foot-wall 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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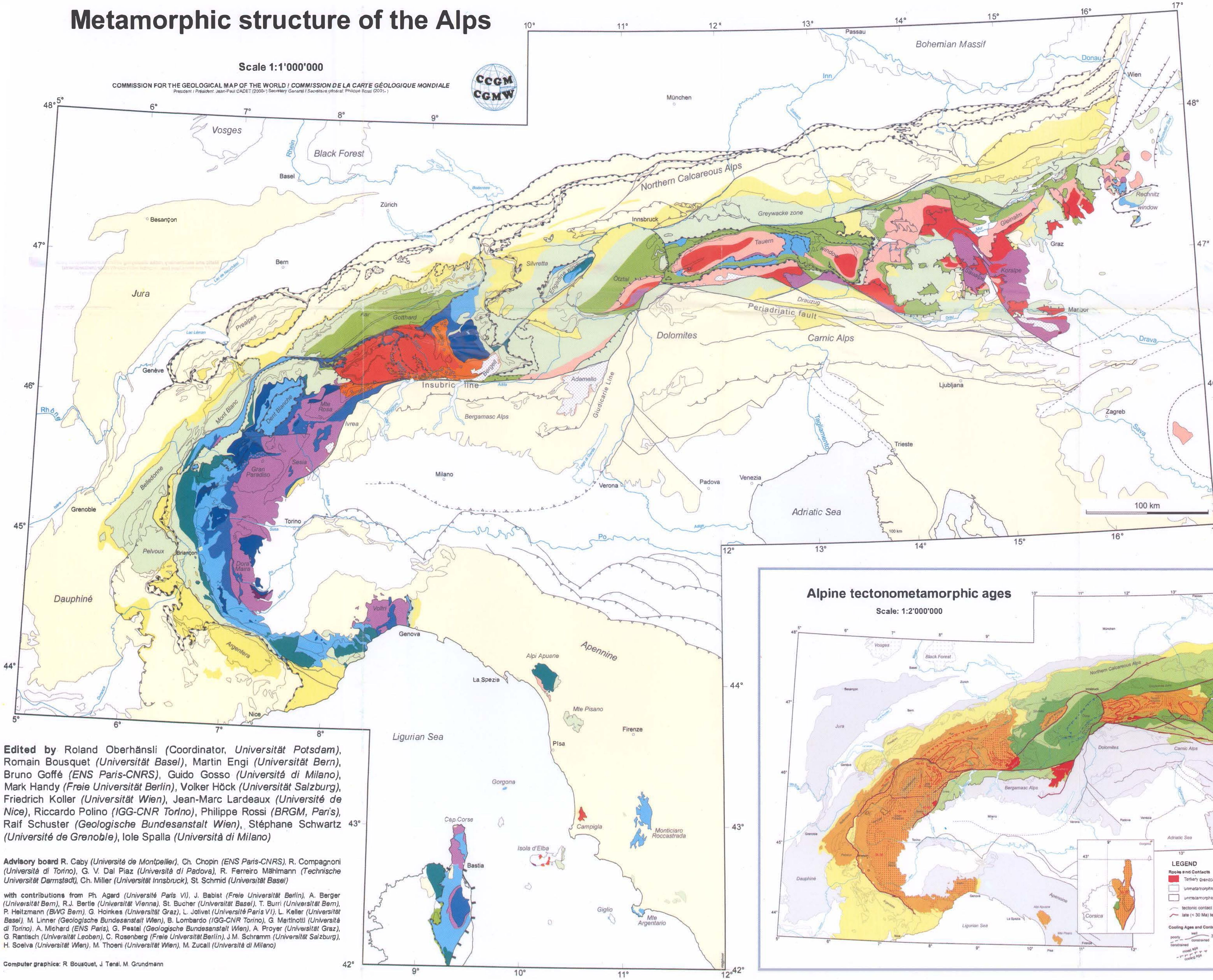

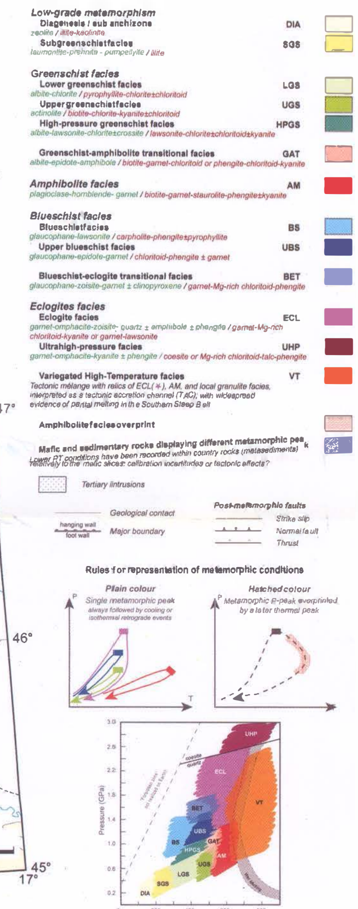

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