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Alpine metamorphism of the Central Alps

by *Martin Frey*[1] and *Rafael Ferreiro Mählmann*[1]

Abstract

The Helvetic nappes of Switzerland comprise a continuous zone of very low-grade metamorphism of up to 15 km width. In general, metamorphic grade increases within a single tectonic unit from the external part towards the internal part and increases within the nappe stack from top to bottom. However, an inverted metamorphic pattern is observed in several places. Physical conditions attending very low-grade metamorphism (= anchizone) of the Helvetic nappes correspond to a temperature range of c. 240–300 °C at pressures of c. 2–3 kbar. This Tertiary metamorphic evolution was diachronous and presumably occurred between c. 35 and 15 Ma. *The Aar and Gotthard basement massifs* were affected by greenschist facies metamorphism during Tertiary time. Within the Aar massif, with increasing Alpine metamorphic grade, the first appearance of green biotite, the disappearance of stilpnomelane and the microcline/sanidine transformation isograd have been mapped in metagranitoids. The oligoclase zone boundary in granitic gneisses is located in the middle of the Gotthard "massif". Physical conditions attending Alpine greenschist facies metamorphism of the two massifs are best constrained by fluid inclusion data from fissure quartz. For the Grimsel area, southern Aar massif, 450 °C / 4.4 kbar are indicated by the earliest fluid inclusion population. The *Penninic Prealps* cover nappes contain several tectonic units showing very low-grade metamorphism including the Gêts nappe in the Chablais of France, the Préalpes Médianes nappe and the Niesen nappe, in the Préalpes Romandes of Switzerland. *The Lepontine area* of amphibolite facies grade shows a rather simple P-T distribution pattern. Temperature increases from 500 to 550 °C at the limit of amphibolite grade metamorphism in the north and west, to c. 675 °C towards the south at the Insubric line. Maximum recorded pressures of c. 7 kbar are in a central region c. 20 km north of the Insubric line, and decrease both to the north (5.5 kbar) and south (4.5 kbar). The timing of the climax of this metamorphism remains poorly known, but deeply-buried rocks reached their peak presumably between 27 and 33 Ma. High-pressure relics are preserved in the Adula-Cima Lunga nappe with inferred P-T conditions of 15–50 kbar / 600–1100 °C. In the Cima Lunga unit this very high-pressure metamorphism reached peak temperature conditions at c. 35 Ma. In *the Simplon area* the effects of the Tertiary Alpine metamorphism are best documented in calcareous schists (Bündnerschiefer). Along a cross-section between Brig (middle greenschist facies) and Crevola (middle amphibolite facies), the following mineral zone boundaries and isograds could be mapped with increasing grade: first appearance of biotite + calcite, garnet and Ca-amphibole, respectively; paragonite + calcite + quartz-out isograd, margarite + calcite + quartz-out isograd, scapolite-in zone boundary, and muscovite + calcite + quartz-out isograd. Along this cross-section, P-T data increase from 2–3 kbar / 400–420 °C to 6–8 kbar / 580–620 °C. *The Penninic units east of the Lepontine area* were predominantly metamorphosed under high-pressure greenschist facies conditions in early Tertiary time. However, blueschist facies relics are preserved in the NE part of the Adula nappe and rare (Fe,Mg)-carpholite is present in the Bündnerschiefer of northern Graubünden. *The boundary region between Central and Eastern Alps in Graubünden* shows a complicated metamorphic pattern of subgreenschist to lower greenschist facies conditions. This pattern is mainly controlled by the burial depth in the nappe pile and the presence of different phases of metamorphism, i.e. an oceanic metamorphism of Jurassic age and two phases of orogenic metamorphism of Upper Cretaceous and Tertiary age, respectively. In *the Bergell area*, orogenic metamorphism in the Gruf complex is documented by a P-T-t path culminating under granulite facies conditions (> 800 °C / 10 kbar). In the adjacent Chiavenna ophiolite, a sequence of closely spaced isograds indicates a metamorphic field gradient of 40–50 °C/km, attributed to the rapid exhumation of the high-grade Gruf complex. At the eastern margin of the Bergell pluton, contact metamorphism is well documented by four isograds in serpentinites and two isograds in metapelites.

Keywords: Central Alps, Alpine metamorphism, low-grade metamorphism, P-T-t path.

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1. Introduction

This communication deals with the Alpine metamorphism of the Central Alps located between the Eastern and Western Alps. The limit between the Central and Eastern Alps is a clearly defined tectonic boundary where the Penninic units disappear below the Austroalpine units in the eastern part of Switzerland. The limit between the Central and Western Alps is less clearly defined because major tectonic units continue from France and Italy into Switzerland. Traditionally, this limit is set at the border between France and Switzerland.

The aim of this paper is to provide an explanatory text for the Alpine Metamorphic Map of the Central Alps, and as such it reviews our present knowledge on Alpine metamorphism of the Central Alps. It may be interesting, however, to point out some milestones in the history of research concerning the Alpine metamorphism of the Central Alps. Relevant data are summarized in table 1. It is surprising to note that this research started so late considering that G. BARROW mapped zones of progressive regional metamorphism of the Scottish Highlands in 1893. The key to this is that major parts of the Alps consist of pre-Triassic polymetamorphic basement which prevented early recognition of the relatively simple patterns of Alpine metamorphism.

In the following sections, the Alpine metamorphism of the Helvetic, Penninic and Penninic plus Austroalpine units of the boundary region between Western and Eastern Alps will be summarized. For each tectonic unit, information on the following items is provided: rock types; index minerals and important mineral assemblages, metamorphic facies; P-T estimates and data on P-T-d path if available; geochronologic data relevant to metamorphism; and interpretation(s) of the tectono-metamorphic history. Names of tectonic units and localities mentioned in the text are found in figure 1.

Tab. 1 Some landmarks of research on Alpine metamorphism of the Central Alps.

1960	First distribution map for some rock-forming minerals (Stp, Cld, Na–Am, Ky, Sil) of Alpine, Tertiary metamorphism (NIGGLI, 1960)
1962	Use of the An-content of plagioclase as an index of metamorphism (WENK, 1962)
1965	Distribution maps for some minerals of Alpine metamorphism (Stp, Na–Am, Cld, St, Ky, Sil) (NIGGLI and NIGGLI, 1965)
1965	Progressive metamorphism of siliceous carbonates and first mapping of an isograd pertaining to the reaction Tr + 3 Cal + 2 Qtz = 5 Di + 3 CO_2 + H_2O (TROMMSDORFF, 1966)
1969	Progressive metamorphism of a single pelitic and marly formation from diagenesis to amphibolite facies (FREY, 1969)
1973	Metamorphic map at a scale of 1:1'000'000 (NIGGLI and ZWART, 1973)
1974	Progressive metamorphism of ultramafic rocks (TROMMSDORFF and EVANS, 1974)
1974–76	Mapping of three-dimensional isograds, (STRECKEISEN and WENK 1974; FOX, 1975; THOMPSON, 1976)
1980	First P-T estimates along the Swiss Geotraverse Basel–Chiasso (FREY et al., 1980b)
1983	First quantitative P-T path (BUCHER and DROOP, 1983)
1987	First pressure-temperature-deformation path (LÖW, 1987)
1995/97	First maps of isotherms and isobars of Tertiary metamorphism for the Lepontine area (ENGI et al., 1995; TODD and ENGI, 1997)

Abbreviations

Mineral abbreviations are after KRETZ (1983); see also extension in BUCHER and FREY (1994). In addition: Olg = oligoclase.

IC Illite crystallinity p.f.u. per formula unit
VR Vitrinite reflectance

2. Helvetic nappes

The Helvetic nappes are cover nappes, comprising mainly Jurassic, Cretaceous and Eocene rocks; in the Glarus Alps also Permian "Verrucano" and Triassic. The Mesozoic sediments making up the largest part of the Helvetic nappes comprise essentially a carbonate shelf sequence of the European margin.

A continuous zone of very low-grade metamorphism of up to 15 km width extends from the

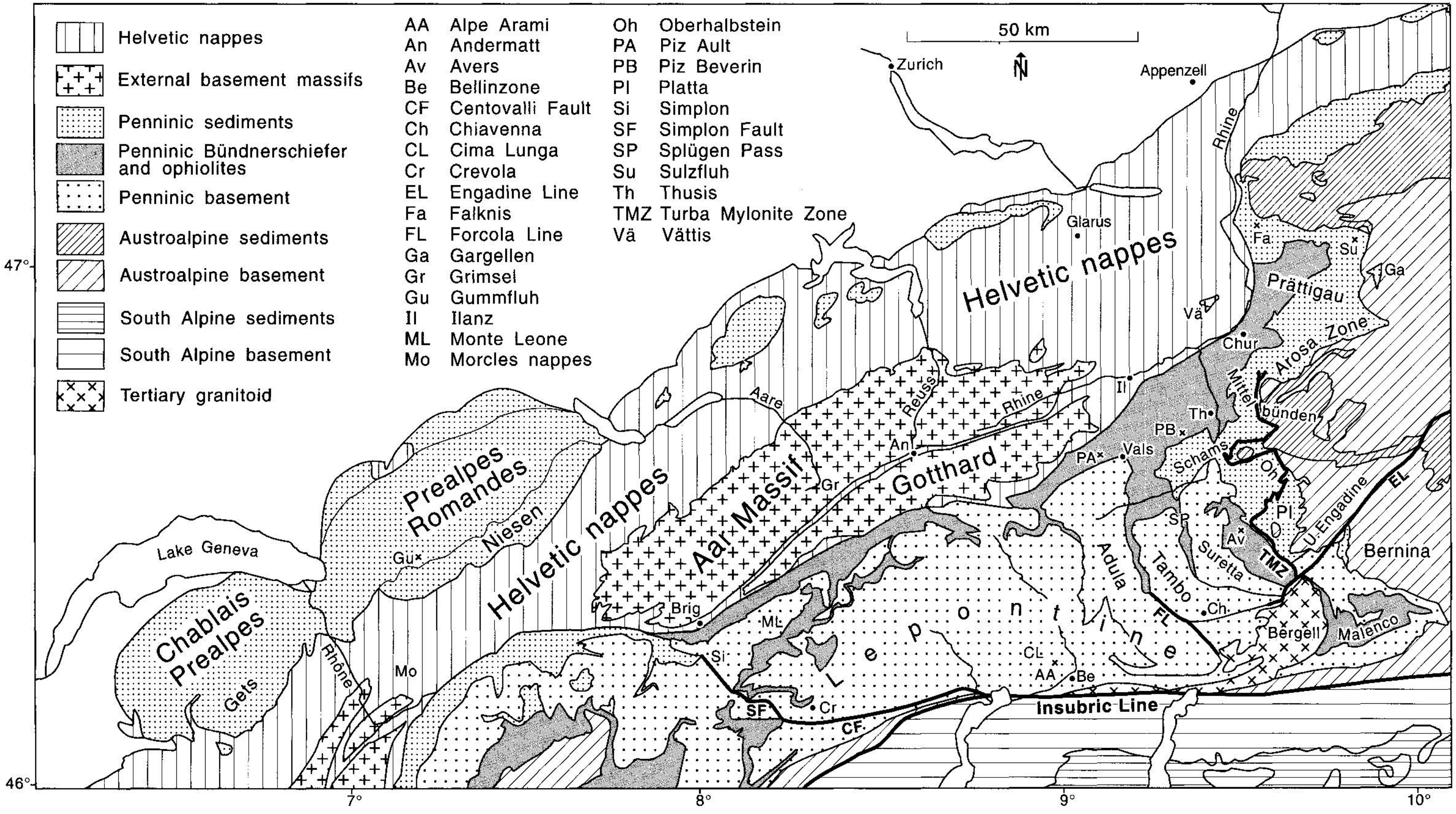

Fig. 1 Tectonic sketch map of the Central Alps showing main tectonic units and localities mentioned in the text.

lower Rhone valley in the SW to the upper Rhine valley in the NE. The delineation of this zone is based on illite crystallinity data and is, therefore, equivalent to the anchizone. In addition, various index minerals supplemented by vitrinite reflectance and fluid inclusion data have been used to characterize this zone of incipient metamorphism. Very low-grade metamorphism of the Helvetic nappes is now rather well-known, and detailed studies include, progressing from SW towards NE: GOY-EGGENBERGER (1997) in the Morcles nappe; BURKHARD (1988) in the western border area of the Aar massif; BREITSCHMID (1982) in a cross section along the Reuss valley; RAHN et al. (1995, and references therein) in the Glarus Alps; and WANG et al. (1996) in the Helvetic Alps between Appenzell and Chur.

The IC distribution patterns show: (i) that within a single tectonic unit IC values decrease, hence grade increases, from the northwest towards the southeast; (ii) within the stack of Helvetic nappes, IC values decrease downwards; (iii) an inverted metamorphic pattern is present in some places, e.g. in the Reuss valley between upper anchizonal grade in the southern part of the Axen nappe and late diagenetic flysch units of the Infrahelvetic complex (BREITSCHMID, 1982); a similar pattern occurs between the epimetamorphic Verrucano nappe, the lowest Helvetic nappe of the Glarus Alps, and mid-anchizonal flysch units of the Infrahelvetic complex, separated by the Glarus thrust (FREY, 1988; see also ARKAI et al., 1997).

In shales and slates of the anchizone, in addition to illite and chlorite, common minerals include pyrophyllite, Na,K-mica, and paragonite (e.g. WANG et al., 1996; LIVI et al., 1997). The pyrophyllite isograd pertaining to the reaction Kln + Qtz = Prl + H_2O after FREY (1987) is indicated on the map of Alpine metamorphism (Fig. 2). Chloritoid is known from a few localities in the internal part of the Helvetic nappes of western Switzerland, mainly from the epizone but possibly also from the upper anchizone (BURKHARD, 1988; GOY-EGGENBERGER, 1997) and south of the Vättis window (WANG et al., 1996).

In the andesitic Lower Oligocene Taveyanne greywacke of the Helvetic Alps a sequence of zeolite, prehnite-pumpellyite, pumpellyite-actinolite, and lower greenschist facies assemblages has been recognised (RAHN et al., 1994; SCHMIDT et al., 1997, and references therein). Some typical mineral assemblages, always with additional Ab + Chl + Qtz + Cal + Ttn are: Lmt ± Cor ± Prh ± Pmp, Prh + Pmp ± Ep, Pmp + Act + Ep, Act + Ep. Some occurrences of the index minerals laumontite, prehnite and pumpellyite are shown on the map.

In glauconite-bearing limestones of Cretaceous and Tertiary age, the following mineral sequence is observed with increasing grade (FREY et al., 1973; BREITSCHMID, 1982; WANG et al., 1996): Glt ± Chl, Glt + Stp + Kfs ± Chl, Stp + Kfs ± Chl, and Bt + Stp + Kfs. Two isograds have been mapped in the Glarus Alps, a stilpnomelane isograd in the low anchizone and a biotite isograd close to the anchizone/epizone boundary.

Physical conditions attending very low-grade metamorphism of the Helvetic nappes have been derived by a variety of methods including phase equilibria, calcite-dolomite, chlorite, coal rank and stable isotope thermometry, fluid inclusion thermobarometry, and K-white mica *b* cell dimensions. The zone of very low-grade metamorphism (= anchizone) corresponds to a temperature range of c. 240–300 °C at pressures of c. 2–3 kbar, i.e. this metamorphism is of the medium pressure type.

In the Helvetic nappes, both the transition from the late diagenetic zone to the anchizone and the pyrophyllite isograd crosscut nappe boundaries, indicating that nappe transport took place mostly before regional metamorphism. In the parautochthonous components of the Infrahelvetic complex east of the Aar Massif, stilpnomelane (BÜRGISSER and FELDER, 1974) and chloritoid (PFIFFNER, 1982) neoblasts overgrow the schistosity generated by the Calanda movement phase, indicating that the metamorphism postdates the main deformation.

The timing of the tectono-metamorphic history of the Helvetic nappes is constrained by chronostratigraphic and radiometric data (HUNZIKER et al., 1986; HUON et al., 1994; and references therein). According to chronostratigraphic data, the youngest sediments deposited within the Helvetic realm are uppermost Eocene and earliest Oligocene flysch. Final nappe emplacement took place after the Middle Miocene as freshwater Molasse of this age is found in the north beneath the frontal thrusts. This means that a timespan of c. 20 Ma starting at c. 35 Ma was available for deformation and metamorphism. For the Glarus Alps, HUNZIKER et al. (1986) dated the main phase of Alpine metamorphism at 30–35 Ma, based on concordant K–Ar, $^{40}Ar/^{39}Ar$ and Rb–Sr illite ages, while a second age group between 20 and 25 Ma was attributed to movements along the Glarus thrust. For the Helvetic nappes of western Switzerland, HUON et al. (1994) noted a diachronous metamorphic evolution between 37 and 15 Ma, based on K–Ar illite ages.

A synthesis of the data presented above suggests that the Helvetic Alps evolved through a series of tectono-metamorphic events. Sedimenta-

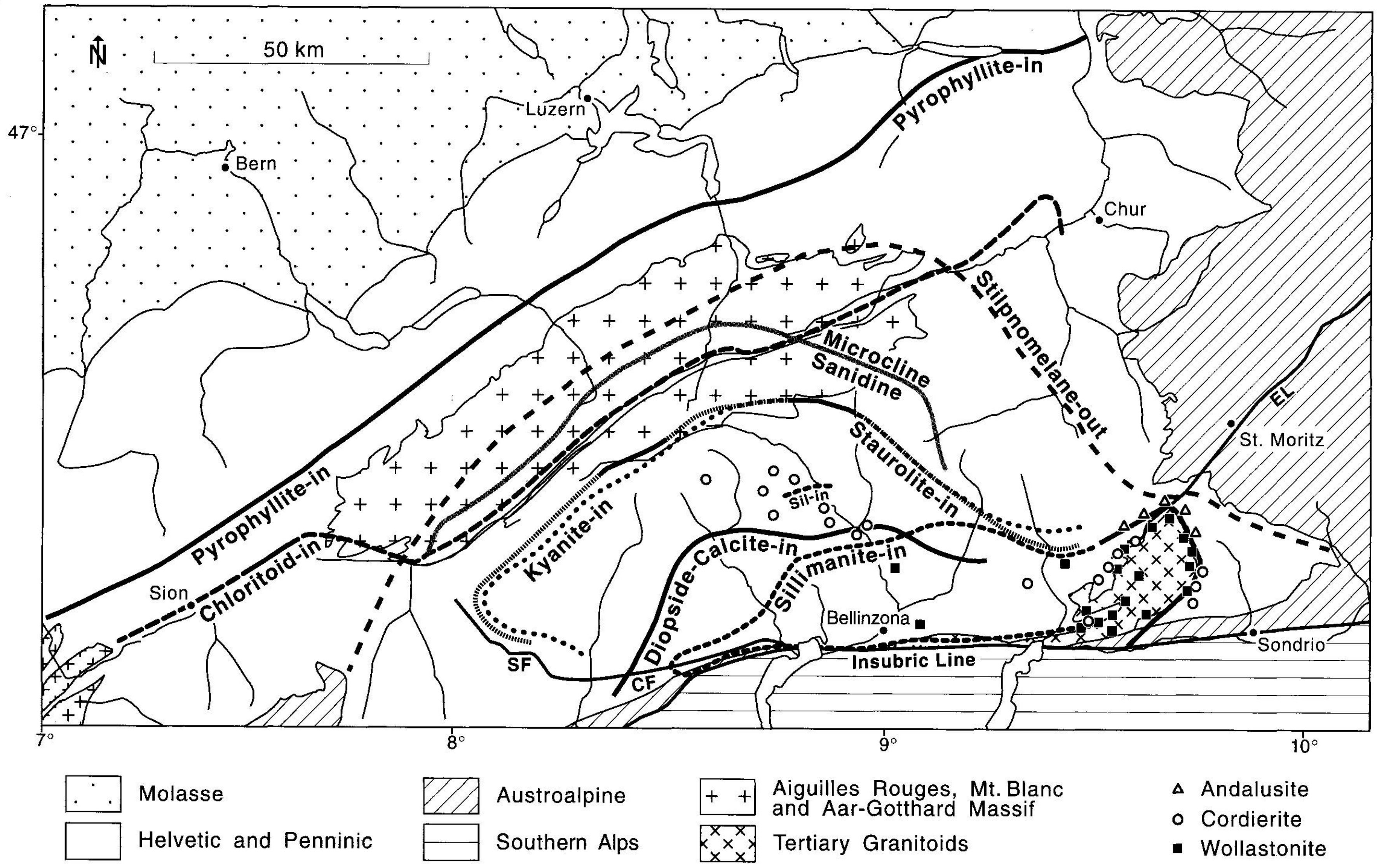

Fig. 2 Selected isograds (solid curves) and mineral zone boundaries (dashed curves) of Alpine metamorphism of the Central Alps, after NIGGLI and NIGGLI (1965), TROMMSDORFF (1980), BERNOTAT and BAMBAUER (1982), IROUSCHEK (1983) and FREY (1987).

tion ended in the Lower Eocene (Helvetic nappes) or Early Oligocene (Infrahelvetic complex). This was rapidly followed by crustal shortening and deformation associated with the development of a southward-dipping subduction zone (MILNES and PFIFFNER, 1977), generating a regional pattern of metamorphic grade progressing from north to south both in the Helvetic nappes and in the Infrahelvetic complex.

3. Aar massif, Urseren-Garvera zone and Gotthard "massif"

The Aar massif is a large basement massif of the Helvetic domain and consists of Paleozoic to Proterozoic basement rocks with a complex polymetamorphic history (see VON RAUMER et al., 1999, this volume) that were intruded by large volumes of late-orogenic intrusives of Upper Carboniferous age, coeval with minor amounts of volcano-sedimentary formations. The Urseren-Garvera zone is a sedimentary zone between the Aar massif and the Gotthard "massif" made up of Late Paleozoic to Upper Jurassic formations, which represent the overturned cover of the Gotthard "massif". The Gotthard "massif", formerly regarded as a basement massif of the Helvetic domain, is now considered to be an Infrapenninic nappe. It consists of a sequence of paragneisses and micaschists with embedded mafic, ultramafic and calc-silicate rocks that were intruded by large volumes of granitoids during Late Ordovician and Late Carboniferous.

During Tertiary time, the Aar massif, the Urseren-Garvera zone and the Gotthard "massif" were affected by greenschist facies metamorphism. The Alpine overprint of the basement massifs is best recognized in the monometamorphic late Variscan granitoids or may be derived from the Mesozoic sediments surrounding the massifs. In the Central Aar Granite, a typical Alpine mineral assemblage is Qtz + Ab + Kfs + Bt + Phe + Ep ± Grt (Ca–Mn–Fe) (STECK and BURRI, 1971). Within the Aar massif, the following mineral zone boundaries and isograds have been mapped in metagranitoids with increasing Alpine metamorphic grade: first appearance of green biotite (STECK and BURRI, 1971), disappearance of stilpnomelane (JÄGER et al., 1967), and the microcline/sanidine transformation isograd (BAMBAUER and BERNOTAT, 1982; BERNOTAT and BAMBAUER, 1982; Fig. 2). Additional features on Alpine metamorphism of granitoids from the Aar massif are summarized in FREY et al. (1980b).

Metamorphosed Mesozoic sediments of the Urseren-Garvera zone are characterized by chloritoid-bearing assemblages. In the Upper Triassic a typical mineral assemblage is Ms + Pg + Cld + Chl + Qtz + Rt, and the formation of chloritoid may be due to the consumption of chlorite + hematite (FREY, 1974). In the Liassic the maximum mineral assemblage is Ms + Pg + Mrg + Cld + Chl + Qtz + Cal + Dol + Py + Rt + Gr, and the formation of chloritoid and margarite may be due to the consumption of pyrophyllite + chlorite and pyrophyllite + carbonates, respectively (FREY, 1978; LIVI et al., 1997). In metamorphosed Permian arkoses the assemblage Qtz + Ab + Kfs + Bt + Phe + Ep + Grt (Ca–Mn–Fe) is observed near Hospental, 3 km SW of Andermatt (STECK and BURRI, 1971; STECK, 1976).

In the northwestern part of the Gotthard "massif", oligoclase first appears in granitic gneisses and albite + oligoclase coexist over large areas of this "massif" due to the presence of the peristerite gap in the plagioclase series (STECK, 1976). A typical Alpine mineral assemblage in Late Carboniferous metagranitoids is Qtz + Ab + Olg + Kfs + Bt + Phe + Chl + Ep + Grt (Ca–Mn–Fe) + Cal + Mag (STECK, 1976).

Physical conditions attending greenschist facies metamorphism of the Aar massif, the Urseren-Garvera zone and the Gotthard "massif" are not well constrained. Some information is available from fluid inclusions, but the derived PT data should be regarded as minimum values for orogenic metamorphism. For the Aar massif, temperatures calculated from K/Na ratios of early fluid populations yielded a range of 405–450 °C and pressures, calculated for a constant temperature of 400 °C, were between 2.7 and 3.8 kbar (POTY et al., 1974; MULLIS et al., 1994). A pressure-temperature-time path for fissure quartz from Zinggenstock of the Grimsel area, southern Aar massif, indicates 450 °C / 4.4 kbar at c. 19 Ma for the earliest and 300 °C / 2.4 kbar at c. 14 Ma for the latest fluid inclusion population (MULLIS, 1996). Similar data from an Alpine fissure from La Fibbia, located at the southern border of the Gotthard "massif", yielded 420 °C / 3.3 kbar at c. 20 Ma for the earliest and 240 °C / 1.8 kbar at c. 17–13 Ma for the latest fluid inclusion population (MULLIS, 1996).

A maximum possible age of metamorphism of 25 Ma was derived from Rb–Sr ages of Alpine phengites in granites of the Grimsel area (DEMPSTER, 1986).

4. Penninic realm

The very low-grade metamorphism of the Prealps is described first. Then the metamorphism of the Lepontine area, the classical Alpine metamorphic realm in the Central Alps, is described. This is followed by a treatment of the Alpine metamorphism west and east of the Lepontine area, respectively.

4.1. PREALPS

The Prealps consist of cover nappes of Triassic to Eocene formations, derived from the Valais, Briançonnais and Piemont belts. Very low-grade metamorphism is known from several tectonic units of the Prealps including the Gêts nappe in the Chablais of France, the Préalpes Médianes nappe and the Niesen nappe, in the Préalpes Romandes of Switzerland. The methodology used is the same as for the Helvetic nappes (see above).

In the Gêts nappe, incipient metamorphism is indicated by anchizonal illite crystallinity from schistose sediments (CARON and WEIDMANN, 1967, p. 394), the presence of stilpnomelane in granite and of actinolite, epidote, prehnite, pumpellyite, sodium amphibole (not specified) and stilpnomelane in diabase, gabbro and rodingite (BERTRAND, 1970, 1980). Age and origin (oceanic and/or orogenic?) of this metamorphism are not known.

In the Préalpes Médianes nappe, the degree of metamorphism increases from late diagenesis in the external part to epizonal conditions in the internal part, based on IC data (MOSAR, 1988; JABOYEDOFF and THÉLIN, 1996). Various index minerals have been noted including diaspore, pyrophyllite, Na,K-mica, paragonite, and corrensite (JABOYEDOFF and THÉLIN, 1996, and references therein). The main metamorphic event affected the Préalpes Médianes nappe during transport from their Penninic origin, and the process responsible for this Alpine metamorphism was progressive burial by thrust stacking, probably during the Late Eocene (JABOYEDOFF and THÉLIN, 1996). However, in the marble mylonite at the base of the Gummfluh klippe, the main geologic episode recorded in the $^{40}Ar/^{39}Ar$ age spectra of white micas is of Late Cretaceous/early Tertiary age (64–80 Ma). Thus this mylonite appears to be a Cretaceous thrust plane and not the thrust surface formed during transport of the klippe into its present position from the Penninic Alps during the Tertiary (COSCA et al., 1992).

In the Niesen nappe, the upper part belongs to the late diagenetic zone whereas the main part records anchizonal conditions, based on IC, VR and fluid inclusion data (FREY et al., 1980; MOSAR, 1988, and references therein). In the Infra-Niesen zone, a complex tectonic unit located below the Niesen nappe and above the Helvetic nappes, upper anchizonal conditions are present (LEMPICKA MÜNCH, 1996). The inverse metamorphic discontinuity between the Infra-Niesen zone (upper anchizone) and the underlying Ultrahelvetic Laubhorn nappe (late diagenesis) implies that the very low-grade metamorphism has been transported over the footwall.

4.2. LEPONTINE AREA

The term of "Lepontinic gneiss region" was coined by WENK (1956) for the deepest part of the Alps showing a specific structural style linked to high grades of Tertiary metamorphism. This region extends from the Gotthard "massif" in the north to the Insubric line in the south and from the Simplon area in the west to the Bergell area in the east. Pre-Triassic basement rocks of various nappes are separated, at least in part, by Mesozoic formations.

On the map of Alpine metamorphism the Lepontine area is easily recognized by an extensive realm of amphibolite facies grade. The greenschist/amphibolite facies boundary was drawn according to the staurolite isograd for traditional reasons except southwest of the Simplon fault, where staurolite is missing, presumably for chemical reasons. In this region, the albite-oligoclase transition was used to define the lower limit of the amphibolite facies (COLOMBI, 1989, Fig. 6–2D). If the greenschist/amphibolite facies boundary were drawn according to the plagioclase (An 17) – hornblende isograd in mafic rocks, this would result in a slightly extended area of amphibolite facies grade (see STECK and HUNZIKER, 1994, Fig. 4). The rather simple pattern of isograds and mineral zone boundaries of the Lepontine area has been described extensively in literature (e.g. TROMMSDORFF, 1966; FREY et al., 1974; TROMMSDORFF, 1980; STECK and HUNZIKER, 1994) and is summarised in figure 2.

The relationship between crystallization and deformation is well studied in the Lepontine area. The thermal peak of amphibolite facies metamorphism postdated nappe formation because isograds are crosscutting through major nappe boundaries (e.g. TROMMSDORFF, 1966, p. 447; WENK, 1970). Detailed structural work in the Lower Penninic zone has shown that the main thermal event occured after the first Alpine deformation phase that led to a complex imbricate nappe structure as the result of overthrusting and recumbent folding, but during the second, main post-nappe folding phase and during the third deformation phase producing cross-folds (GRUJIC and MANCKTELOW, 1996, and references therein).

Based on extensive regional correlations, GRUJIC and MANCKTELOW (1996) tentatively concluded that the second and third deformation phases, and hence also the thermal peak, took place between 35 and 30 Ma.

The regional P-T distribution pattern of the Lepontine area is now rather well known (ENGI et al., 1995; TODD and ENGI, 1997), based on a thermobarometric study of 116 samples. Peak temperatures increase from 500 to 550 °C along the limit of amphibolite grade metamorphism in the north and west, to c. 675 °C toward the south at the Insubric line near the town of Bellinzona. Maximum recorded pressures of c. 7 kbar are in a central region c. 20 km north of the Insubric line, and decrease both to the north (5.5 kbar) and south (4.5 kbar). Some isotherms and isobars are shown on the map. As pointed out by ENGI et al. (1995), these isotherms and isobars do not imply a synchronous P-T distribution during the orogenic evolution of the Lepontine area.

Despite much effort, reviewed recently by HUNZIKER et al. (1992) and STECK and HUNZIKER (1994), geochronological evidence giving a reliable measure of the timing of the metamorphic peak in the Lepontine area is still scarce. Rb–Sr phengite data at 35–38 Ma from the Monte Rosa and Mischabel nappes to the west and the Suretta nappe to the east of the Lepontine have been interpreted by HUNZIKER (1969) as the time of the culmination of the Tertiary metamorphism. However, in an orogenic belt different vertical levels

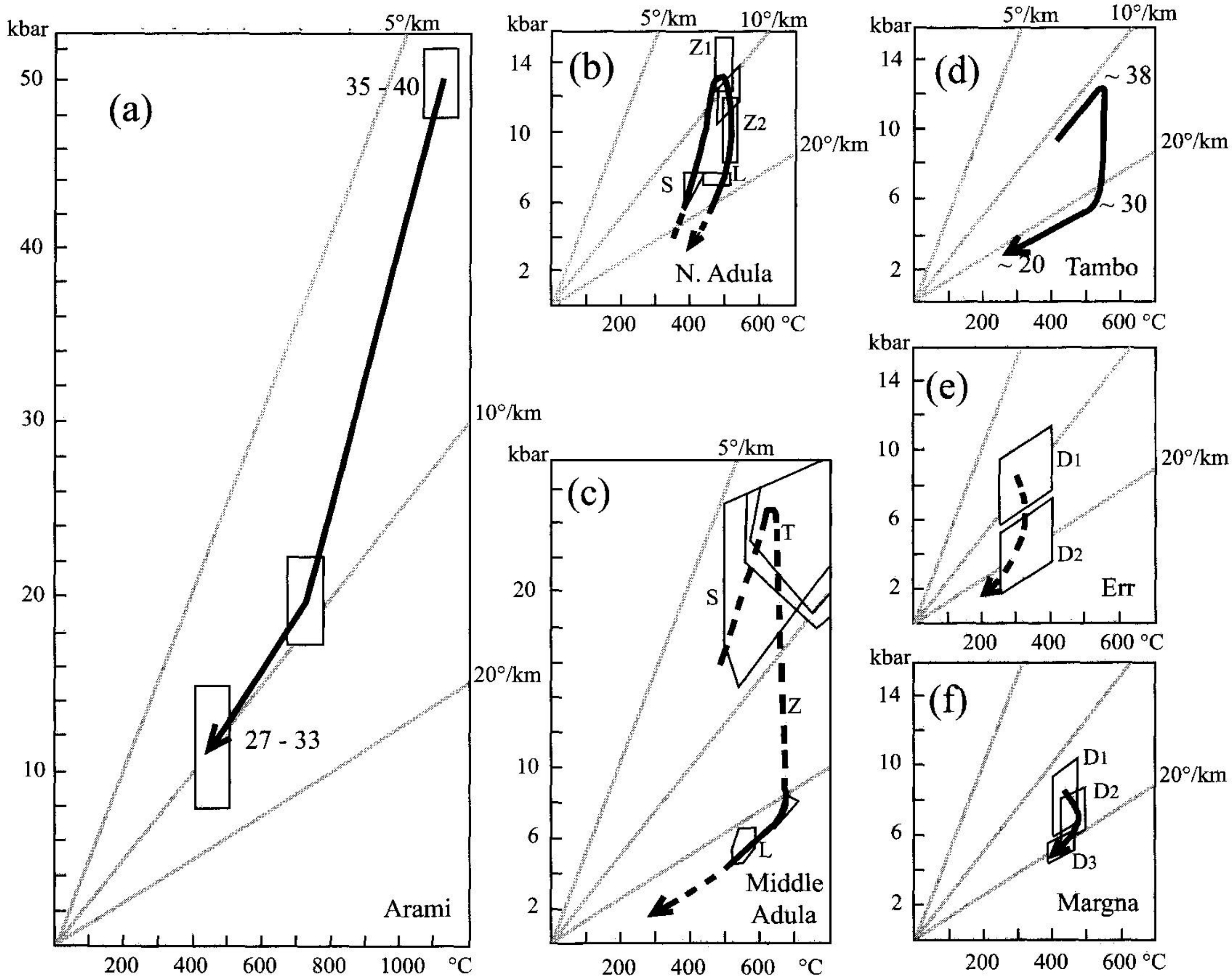

Fig. 3 Selected PT path data from the Central Alps. Locations are shown in figure 1. (a) Alpe Arami, garnet-peridotite body (BRENKER and BREY, 1997) with radiometric age data from GEBAUER (this volume) (b) Northern Adula nappe (LÖW, 1987); S, Z1, Z2 and L refer to successive deformation phases. (c) Middle Adula nappe (PARTZSCH and MEYRE, 1995; MEYRE et al., 1997); S, T, Z and L refer to successive deformation phases. (d) Tambo nappe (MARQUER et al., 1994). (e) Base of the Err nappe (HANDY et al., 1996); D1 and D2 refer to successive deformation phases. (f) Part of the Margna nappe south of the biotite isograd (HANDY et al., 1996); D1-D3 refer to successive deformation phases.

and different geographic domains reach their peak of metamorphism at different times and, therefore, a single age for the thermal peak of metamorphism over large parts of the Alps is unlikely (D. Vance, written communication 1998). A Sm–Nd age of 26.7 ± 1.7 Ma on garnet from the Castione quarry NNE of Bellinzona was interpreted to date the climax of the metamorphism (VANCE and O'NIONS, 1992). Based on U-Pb zircon and titanite data from the southern part of the Lepontine area, GEBAUER (1999, this volume) argues that T_{max} was reached some 32–33 Ma ago.

High-pressure relics are preserved in a few places of the Lepontine area. On the map of Alpine metamorphism, some eclogite occurrences are indicated within the area of amphibolite facies grade and come from the Antrona zone and the Furgg zone (COLOMBI and PFEIFER, 1986), the Cima Lunga unit (PFIFFNER and TROMMSDORFF, 1998, and references therein), and the Adula nappe (HEINRICH, 1986). Inferred P-T conditions for these metabasites range from > 14 kbar / 500–700 °C for the Antrona zone (COLOMBI and PFEIFER, 1986) and 15–35 kbar / 600–900 °C for the Cima Lunga-Adula nappe complex (HEINRICH, 1986). For the garnet-peridotite body of the Alpe Arami, peak metamorphic conditions were estimated as 50 ± 2 kbar/1120 ± 50 °C and the exhumation path has been reconstructed (Fig. 3a) for this mantle slice (BRENKER and BREY, 1997). Until recently, a Late Cretaceous or eo-Alpine age had been assumed for these high- and ultrahigh-pressure rocks (e.g. FREY et al., 1980b; STECK and HUNZIKER, 1994). However, according to recent radiometric dating the very high-pressure metamorphism of the Cima Lunga unit is of Eocene age (GEBAUER, 1999, this volume).

Various interpretations have been proposed for the metamorphic high of the Lepontine area. (i) Thermal doming under a cover of 10–25 km was assumed by WENK (1970). (ii) By contrast, NIGGLI (1970) concluded that the regional metamorphism in the Simplon-Ticino region may be interpreted as a load metamorphism caused by tectonic burial of 15–30 km during the formation of the Alpine nappes in Upper Cretaceous to early Tertiary time. (iii) BRADBURY and NOLEN-HOEKSEMA (1985) attributed the cause of Lepontine metamorphism to overplating of the Penninic complex by the Austroalpine mass at ?60 Ma whilst a two-stage underplating model at 22 and 10 Ma was found to be consistent with the excavation history of the Lepontine. (iv) BECKER (1993) suggested that the emplacement of the hot Cima Lunga slab onto lower Penninic units to be the primary cause for the middle Tertiary Barrovian-type metamorphism in the Central Alps. (v) ENGI et al. (1995) proposed that the metamorphic field gradients and age determinations are consistent with two stages of metamorphism. The first stage created the P-T pattern in the northern Lepontine during south-dipping continental subduction in which T_{max} was reached at 35–38 Ma. The second stage affected only the south-eastern part of the Lepontine and occurred when the hot Cima Lunga lid (following BECKER, 1993) and magmatic bodies, at least in the Insubric area, were thrusted onto the lower Penninic stack at around 30 Ma; here T_{max} was reached between 28 Ma (south) and 20 Ma (central part). (vi) VON BLANCKENBURG and DAVIES (1995) proposed the slab breakoff model to explain the temporal and spatial link between magmatism and uplift and exhumation during late Tertiary convergence in the Alps. Two possible sources of advective heat were identified, namely the plutons and dykes emplaced along a prominent fault zone, the Periadriatic Lineament; and rising HP slices, like the Cima Lunga-Adula nappe complex, that were probably expelled along the former subduction thrust. At present, this model appears to be the most promising one because it is in accordance with petrologic field data and geochronologic data.

4.3. PENNINIC UNITS WEST OF THE LEPONTINE AREA

In this section, only the Alpine metamorphism of the Simplon area is treated. Tectonic units west of the Simplon Line, including the Grand Saint-Bernard super-nappe, the Monte Rosa nappe, the Zermatt zone and the Dent Blanche nappe, are treated by DESMONS et al. (this volume).

4.3.1. Simplon area

The Simplon area, located at the western end of the Lepontine, lies within the lower units of the Penninic nappes. The nappe pile consists of polymetamorphic basement with much thinner intercalations of Mesozoic cover separating the various nappe sheets. The Alpine metamorphism is best studied in the Mesozoic cover consisting of calcareous schists with minor marble, dolomite, quartzite and pelite.

The effects of the Tertiary Alpine metamorphism on calcareous schists (Bündnerschiefer or schistes lustrés) were studied in detail along a cross-section between Brig (middle greenschist facies) and Crevola (middle amphibolite facies) by FRANK (1983). The following mineral zone boundaries and isograds could be mapped with increasing grade: first appearance of biotite + calcite, garnet and Ca-amphibole, respectively; paragonite + calcite + quartz-out isograd, margarite + calcite + quartz-out isograd, scapolite-in zone boundary, and muscovite + calcite + quartz-out isograd. Along this cross-section, P-T data increase from 2–3 kbar / 400–420 °C near Brig to 6–8 kbar / 580–620 °C at Crevola. However, the pressure estimate near Brig may be too low because pressure-dependent mineral equilibria were absent in the samples studied by FRANK (1983). The climax of metamorphism was dated using Bündnerschiefer garnet (U–Pb and Rb–Sr methods) from near the staurolite isograd at c. 30 Ma with a garnet growth interval of 2.9 ± 1.5 Ma (VANCE and O'NIONS, 1992).

On Simplon pass, the greenschist/amphibolite facies boundary as shown on the map of Alpine metamorphism is offset by 2–3 km by the Simplon fault zone. As mentioned earlier, this facies boundary was drawn according to the staurolite isograd (NE of the Simplon line) and the albite-oligoclase transition (SW of the Simplon line). If the albite-oligoclase boundary is considered on both sides of the Simplon line, this results in a horizontal sinistral offset of c. 18 km (MANCKTELOW, 1990).

Evidence for the presence of relics of high-pressure metamorphism in the northern Simplon area was presented by HAMMERSCHMIDT and FRANK (1991). White K-micas in the assemblage Phe + Bt + Kfs + Pl + Qtz from granitic gneisses of the frontal part of the Monte Leone nappe are highly phengitic (up to 3.6 Si p.f.u.) indicating pressures of up to 13 kbar. These data were interpreted by HAMMERSCHMIDT and FRANK (1991) to reflect conditions of the Eo-Alpine metamorphism although no radiometric data were given to support this conclusion.

4.4. PENNINIC UNITS EAST OF THE LEPONTINE AREA

In the following section, the Alpine metamorphism of some basement nappes is described first, progressing from west to east or from lower to higher tectonic units. This is followed by treatment of cover units presently located mainly north of the above-mentioned basement nappes.

4.4.1. Northern and Middle Adula nappe

The lower Penninic Adula nappe is the largest basement nappe in the eastern part of the Central Alps, with an estimated thickness of 2–4 km and a north-south extension of some 50 km. The Adula nappe consists predominantly of pre-Mesozoic granitic gneisses and metapelitic micaschists with minor amounts of basic and ultrabasic rocks, as well as metamorphosed Mesozoic marls, limestones, dolomites and sandstones. The structurally middle and upper part of the nappe shows a striking imbricated structure.

The Alpine metamorphism of the Southern Adula nappe and the Cima Lunga unit, the western extension of the Adula nappe, are treated in section 4.2. dealing with the Lepontine area. The Alpine metamorphism of the Gruf complex is treated in section 5.1. dealing with the Bergell area. In the following section, only the Alpine metamorphism of the Northern and Middle Adula nappe are discussed. First, some important results are summarized in chronological order. This is followed by more detailed information on the Alpine metamorphism of the Northern and Middle Adula nappe.

Based on a meticulous petrographic study, VAN DER PLAS (1959) recognized the plurifacial nature of Alpine metamorphism for the Northern Adula nappe. HEINRICH (1986) documented the regional character of a high-pressure metamorphic event of the Adula nappe for the first time and recorded a continuous increase in P-T conditions from about 12 kbar and 500 °C or less in the north of the nappe to more than 20 kbar / 800 °C in the south. Combining structural studies with metamorphic petrology, LÖW (1987) and PARTZSCH and MEYRE (1995) carried out tectono-metamorphic studies in the Northern and Middle Adula nappe, respectively, and derived pressure-temperature-deformation paths.

In the northeastern part of the nappe, in the area of Vals-Zervreila, metabasites are mineralogically variable and were collectively named "amphibolites and allied rocks" by VAN DER PLAS (1959). Based on detailed petrography of metabasites mainly, this author distinguished three successive phases of Alpine metamorphism, characterized by the following minerals, among others. Phase I: glaucophane, crossite, sodium-pyroxene, garnet, epidote and rutile; Phase II: blue-green amphibole, ferrohastingsite, garnet, albite, epidote, biotite and titanite; Phase III: actinolite, chlorite, green biotite, epidote, zoisite, albite and titanite. Correspondingly, on the map of Alpine metamorphism, the area of Vals-Zervreila is shown in epidote-blueschist facies overprinted in greenschist facies. In metapelites formed during the high-pressure climax, a typical assemblage is Cld + Ky + Grt + Phe + Qtz + Rt ± St ± Pg (LÖW, 1987). The Alpine evolution of the Northern Adula nappe can be divided into four steps of plastic deformation (LÖW, 1987): (i) nappe formation, (ii) nappe transport with strong internal deformation, (iii) recumbent mega-folding of the Adula nappe (core of fold) and surrounding Bündnerschiefer, (iv) upright refolding and open crenulation in the most frontal parts of the nappe. Deformations of steps (i) and (ii) occurred in a high-pressure regime with a pressure climax at 12–15 kbar / 470–540 °C, whereas steps (iii) and (iv) occurred under greenschist facies conditions (LÖW, 1987). The corresponding P-T path is shown in figure 3b.

In the Middle Adula nappe, eclogites are well preserved in mafic lenses within metasedimentary layers. According to HEINRICH (1986), a typical assemblage is Grt + Omp + Am + Qtz + Rt ± Ky ± Phe ± Pg ± Zo (Ep). Amphibole poikiloblasts were considered to be a "primary", peak eclogite phase formed at 550–650 °C / 15–22 kbar for the Trescolmen locality (HEINRICH, 1986) or to belong to a retrograde re-equilibration, still under eclogite facies conditions at c. 700 °C / 19–21 kbar (MEYRE et al., 1997). Rare high-pressure metapelites formed at similar P-T conditions as eclogites (MEYRE et al., 1999). The Alpine evolution of the Middle Adula nappe appears to be different for the structurally upper and lower parts (PARTZSCH and MEYRE, 1995). The structurally upper part underwent five Alpine deformational events, and P-T calculations reveal a clockwise P-T path culminating under eclogite facies conditions as mentioned above (Fig. 3c). In contrast, the structurally lower part of the same nappe complex suffered three Alpine deformational phases and shows no relics of high-pressure assemblages. P-T calculations reveal an anticlockwise metamorphic evolution culminating under amphibolite facies conditions.

The age of Alpine high-pressure metamorphism of the Northern and Middle Adula nappe is still a matter of debate. Some authors postulated a Cretaceous age for the eclogite formation (e.g. STECK and HUNZIKER, 1994). Paleogeographic reconstructions, structural correlations, and geochronologic data from the Cima Lunga unit imply an Eocene age for this high-pressure metamorphism (SCHMID et al., 1998; GEBAUER, 1999, this volume).

4.4.2. Tambo nappe

The Middle Penninic Tambo nappe is located between the Adula nappe (below) and the Suretta nappe (above). The Tambo basement consists mainly of polycyclic paragneisses, intruded in the south by the Permian Truzzo granite. A reduced Mesozoic cover is locally present.

In the Tambo nappe, Alpine metamorphic grade increases from middle(?) greenschist facies in the frontal part in the north to lower to middle amphibolite facies in the southern and southeastern part. This follows from the isograd pattern of the Tertiary metamorphism in the eastern Central Alps (e.g. STECK and HUNZIKER, 1994). Published mineral assemblage data are, however, rare for this nappe (e.g. RING, 1992; BAUDIN and MARQUER, 1993; MAYERAT DEMARNE, 1994). In the northern Tambo nappe, gneissic rocks are composed of Qtz + Wm + Pl (An > 17) + Kfs + Chl + Bt + Ep/Clz ± Grt ± Cld and amphibolites contain blue-green amphibole + Ep/Clz + Zo + Grt + Chl + Bt + Cld + Pl (An < 20) + opaques + Cal/Dol (RING, 1992). Temperatures attending the Tertiary metamorphism of the northern and middle part of the Tambo nappe ranged between c. 400 and 550 °C (BAUDIN and MARQUER, 1993). Pressure conditions prevailing during the two main ductile deformation events were estimated using phengite composition from well defined microstructural sites (BAUDIN and MARQUER, 1993). During the first deformation phase, corresponding to crustal thickening, Si contents of > 3.45 p.f.u. correspond to high pressures between 10 and 13 kbar. During the second deformation, reflecting E–W extension, Si contents of 3.45–3.2 yielded a large spread of pressures between 10 and 5 kbar. In an attempt to date the D2 event, MARQUER et al. (1994) analysed phengites (Rb–Sr) from mylonites of the Truzzo granite which yielded ages of 25–32 Ma. If correctly interpreted as cooling ages, these would indicate a minimum age for the second deformation event of the Tambo nappe, related to strong decompression (Fig. 3d).

4.4.3. Suretta nappe

The Middle Penninic Suretta nappe is situated between the Tambo nappe (below) and Penninic metasediments of Schams and Avers (above). The frontal part of the Suretta nappe consists mainly of the Rofna gneiss, a deformed Permian granite porphyry. To the south, the main body of the nappe is dominated by polymetamorphic metasediments of pre-Triassic age (Timun mass). Mesozoic cover rocks are deeply infolded in the basement mass. The southernmost part of the Suretta nappe is present as roof pendants of the Bergell intrusion.

In the Rofna gneiss, strongly recrystallized during Alpine time, a typical mineral assemblage is Phe + Qtz + Ab + Kfs + Ep + Cal + Ttn (GRÜNENFELDER, 1956), with stilpnomelane also locally present (STEINITZ and JÄGER, 1981). Phengite barometry on Rofna gneiss from Splügen Pass indicates an isothermal decompression from 10.5 ± 1.5 to 6 ± 1 kbar at temperatures around 400–450 °C (CHALLANDES, 1996). Some crossite schists are mentioned from the Timun mass (ZURFLÜH, 1961, p. 81). The single eclogite occurrence in the uppermost Suretta nappe near Innerferrara considered to be of Cretaceous age by STECK and HUNZIKER (1994, Fig. 2) is, based on structural evidence, of pre-Alpine age (BIINO et al., 1997; NUSSBAUM et al., 1998). The first Alpine assemblage from this same metabasite is Gln + Grt + Ep + Ab + Ttn with estimated TP conditions of c. 400–450 °C and 10 kbar, followed by a greenschist facies overprint (NUSSBAUM et al., 1998). In polymetamorphic pelites of the southern Suretta nappe, chloritoid phyllites with the assemblage Cld + Wm + Chl + Qtz + Ab + opaques ± Grt(?) are of Alpine age (WENK, 1974). On the map of Alpine metamorphism, the Suretta nappe up to the Engadine line is shown as greenschist facies. The age of this metamorphism was dated at 35–40 Ma using phengite (Rb–Sr); this age is considered to reflect white mica formation near the peak of metamorphism (STEINITZ and JÄGER, 1981).

4.4.4. Schams nappes

The Middle Penninic Schams cover nappes were detached from their crystalline substratum, part of the present day Tambo and Suretta nappes. Today, the Schams nappes are located below, in front of and above the front of the Suretta nappe. Lithologically, the Schams nappes consist mainly of Mesozoic limestones and breccias and of minor pre-Triassic granitoid gneiss.

In Mesozoic pelitic and calc-pelitic metasediments, the characteristic assemblage Phe + Chl + Qtz + Ab ± Cal ± Stp ± Ep indicates lower greenschist facies metamorphism, with temperatures in the order of 300–425 °C (SCHREURS, 1995). Indications on pressure conditions are missing. Geochronological dating of fine-grained (< 2 μm) white mica, syntectonically grown during the first deformational event D1, yielded K–Ar ages of 30–45 Ma (SCHREURS, 1995). From these data a Paleogene age was concluded for D1, associated with the stacking of the Penninic nappe pile.

4.4.5. Bündnerschiefer of northern Graubünden

A large mass of Bündnerschiefer, low-grade metamorphic shaly-calcareous-terrigenous sediments, is outcropping in northern Graubünden in front of and separating some of the Middle Penninic nappes. In volume, Bündnerschiefer of the North Penninic realm predominate over those of South Penninic origin (e.g. Avers). The main part of the North Penninic Bündnerschiefer of northern Graubünden can be separated into two nappes, the Grava nappe below and the Tomül nappe above, with an estimated total thickness of some 10 km. The main mass of these so-called Misox Bündnerschiefer is of Cretaceous age. Basaltic intercalations of MORB composition within Bündnerschiefer metasediments represent local remnants of Penninic oceanic crust. For more details see e.g TRÜMPY (1980) and STEINMANN (1994).

The mineralogy of the Bündnerschiefer of northern Graubünden is not well known, presumably because of the monotonous and unattractive appearance of these metasediments. Bündnerschiefer from Schams and Domleschg, north and south of Thusis respectively, contain the typical mineral assemblage Ms + Pg + Na,K-mica + Chl + Qtz + Cal + organic material ± Ab ± Dol (THUM and NABHOLZ, 1972). The same assemblage is also predominant in the Piz Ault area in front of the Adula nappe (KUPFERSCHMID, 1977) and in two reference sections of STEINMANN (1994), i.e. Turisch-Tobel (Grava nappe) and Piz Beverin (Tomül nappe) (M. Rahn and M. Frey, unpublished). Based on this information, the Bündnerschiefer of northern Graubünden are shown in greenschist facies on the map. Recently, however, indications of an earlier high-pressure and low-temperature metamorphism have been found. (Fe,Mg)-carpholite occurs as relic hair-like microfibers included in quartz of quartz-carbonate segregations (GOFFÉ and OBERHÄNSLI, 1992). In the Bünderschiefer of northern Graubünden, (Fe,Mg)-carpholite and chloritoid zone boundaries were tentatively mapped by OBERHÄNSLI et al. (1995, Fig. 4), with grade increasing from east (area of Chur) to west (area of Ilanz). In these rocks, the presence of (Fe,Mg)-carpholite indicates minimum pressures of 6–8 kbar at temperatures up to 350 °C (GOFFÉ and OBERHÄNSLI, 1992).

Metabasites intercalated with Bündnerschiefer, e.g. in the Vals-Safien and southern Avers areas, are mainly represented by greenschist and minor metagabbro with the assemblage Chl + Act + Ep + Phe + Ab + Ttn ± Qtz ± Cal ± Di ± Stp (DIETRICH and OBERHÄNSLI, 1976; KUPFERSCHMID, 1977; and references therein). Some epidote-blueschists are also locally present (e.g. OBERHÄNSLI, 1978), and one such area (southern Avers) is indicated on the map. According to petrographic data, these blueschists predate the greenschist facies overprint. For southern Avers, blueschist facies conditions were estimated at 9 to > 12 kbar / 350–400 °C and later greenschist facies conditions at > 2–3 kbar / c. 400 °C (RING, 1992). Blueschist and eclogite in metabasites intercalated with Bündnerschiefer are known from a single locality in the Misox Zone at Neu-Wahli, with estimated peak metamorphic conditions of > 12 kbar / 460–560 °C (RING, 1992).

4.5. THE BOUNDARY REGION BETWEEN CENTRAL AND EASTERN ALPS

In this section, the following areas are considered, proceeding from north to south: Prättigau half-window, Mittelbünden and Oberhalbstein, and Upper Engadine. The Northern Calcareous Alps are treated by HOINKES et al. (1999, this volume).

4.5.1. Prättigau half-window

The core of a large, east-pitching antiform consists of Prättigau Bündnerschiefer (see above) and Prättigau Flysch (Upper Cretaceous to Lower Eocene). These units are overlain by the Middle Penninic cover nappes of Falknis and Sulzfluh (Triassic to Eocene), and finally by the South Penninic Arosa zone, a strongly deformed unit of ophiolites and Middle Jurassic to Middle Cretaceous oceanic sediments.

The *Prättigau Bündnerschiefer* reached lower greenschist facies in their structurally lower part, surfacing in the western central part of the Prättigau half-window, and are surrounded by anchizonal Bündnerschiefer to the north, east and south (THUM and NABHOLZ, 1972; WEH et al., 1996). Metamorphic grade decreases continuously from the Bündnerschiefer to the overlying *Prättigau Flysch.* In the latter anchizonal IC values (THUM and NABHOLZ, 1972) and vitrinite reflectance values (3–5% R_{max}, FERREIRO MÄHLMANN et al., 1992) indicate very low-grade metamorphism. In the *Falknis nappe,* in the area of the type locality, metamorphic grade generally increases from higher tectonic slices (lower anchizone) to lower ones (low epizone), based on a combination of IC, coal rank and fluid inclusion data (FREY et al., 1980; FERREIRO MÄHLMANN, 1994). This indicates a slight "progressive discontinuity in metamorphic grade" (lower grade rocks resting on higher grade rocks but separated by a tectonic discontinuity) between the Prättigau Flysch below and the Falknis nappe above. The *Sulzfluh nappe* at the northeastern and eastern rim of the Prättigau half-window is in the low anchizone and uppermost diagenetic zone, and is generally of slightly lower metamorphic grade than the Falknis nappe. In the Gargellen window, sediments belonging to the Falknis and Sulzfluh nappes also reached the low anchizone (FERREIRO MÄHLMANN, 1994).

Because Eocene sediments are involved in these units, their metamorphism must be of Tertiary age. K–Ar and Rb–Sr data on fine illite fractions indicate lower Tertiary ages (THUM and NABHOLZ, 1972; FERREIRO MÄHLMANN et al., 1998).

The *Arosa Zone* shows a complex metamorphic pattern because imprints of three phases of metamorphism are present: an oceanic metamorphism of Jurassic age and two phases of orogenic metamorphism of Cretaceous and Tertiary age, respectively. (i) Indications of oceanic metamorphism are found in various ophiolitic rocks, e.g. actinolite and diopside (PETERS, 1963), hydroandradite (PETERS, 1965), sulphide mineralization (FRÜH-GREEN et al., 1990), catabitumen and natural coke (FERREIRO MÄHLMANN, 1994). The same event was also documented by stable isotope data (FRÜH-GREEN et al., 1990). An Upper Jurassic age for this oceanic metamorphism is indicated by the $^{39}Ar/^{40}Ar$ date of 160 ± 8 Ma obtained on primary phlogopite from the Totalp peridotite, an age interpreted as the time of manle upwelling, rifting, and oceanic metamorphism (PETERS and STETTLER, 1987). (ii) Some meter to kilometer size slivers of Lower and Upper Austroalpine basement and Permian and Triassic sediments are found within the South Penninic Arosa zone. Lower Austroalpine slivers show high anchizonal to epizonal IC values and R_{max} values of 3.6–5.8% (Tschirpen-Dorfberg fragments at the southern rim of the Prättigau half-window, FERREIRO MÄHLMANN, 1994), i.e. they are clearly of higher grade than the surrounding rocks of the Arosa zone (see below). By analogy with the situation in the Mittelbünden and Oberhalbstein areas (see below) and supported by K–Ar and Rb–Sr data on fine illite fractions (FERREIRO MÄHLMANN et al., 1993, 1998), these Lower Austroalpine slivers experienced an Upper Cretaceous orogenic metamorphism. (iii) The main mass of ophiolitic rocks of the Arosa zone underwent mélange tectonics followed by orogenic metamorphism in lower Teriary time (FERREIRO MÄHLMANN, 1994), contemporary with adjacent units of the Prättigau half-window. Based on IC and VR data, Mid Jurassic to Mid Cretaceous oceanic sediments of the Arosa zone located at the northeastern, eastern and southern rim of the Prättigau half-window are generally of anchizonal grade, with metamorphic grade generally increasing slightly from NE to SW. Ophiolitic metabasites contain mineral assemblages indicative of prehnite-pumpellyite facies (BEVINS et al., 1997).

Summing up, a complicated metamorphic pattern is found in the Prättigau half-window. This may be explained by a folded diagenetic and low-grade zonation followed by thrusting. At the northern rim of the half-window, a progressive discontinuity in metamorphic grade is seen between the Prättigau Flysch and overlying tectonic units. At the northeastern and eastern rim, no such discontinuity is observed. At the southern rim, a discontinuous inverse metamorphic zonation exists between North and Middle Penninic units.

4.5.2 Mittelbünden and Oberhalbstein

In the Mittelbünden and Oberhalbstein area in eastern Switzerland, at the boundary between the Central and Eastern Alps, three tectonic levels (thrust nappe stacks with different thermo-tectonic histories, delimited by a structural discontinuity and metamorphic hiatus) are recognized, namely the upper, middle and lower levels. The upper level consists of the three Upper Austroalpine units: Silvretta nappe, Arosa Dolomite nappe and Rothorn nappe (pre-Triassic basement, Triassic and minor Lower and Middle Jurassic sediments). The middle level includes the units of the Lower Austroalpine (pre-Triassic basement, Permian to Middle Cretaceous sediments) and the South Penninic Platta nappe (Jurassic ophiolites and Lower and Middle Cretaceous sediments). The lower level comprises the North Penninic Arblatsch flysch and Lenzerheide flysch (both of Upper Cretaceous to Eocene age).

The boundaries of the different levels were defined using IC and VR data, and the juxtaposition of only diagenetically altered rocks and newly formed metamorphic mineral assemblages (FERREIRO MÄHLMANN, 1995, 1996). This author demonstrated that in the three levels incipient metamorphism took place at different times, namely: (i) pre-orogenic and late Cretaceous in the upper level; (ii) early to late Cretaceous in the middle level; and (iii) Tertiary in the lower level. The emerging metamorphic pattern supplemented with paleotemperature data (FERREIRO MÄHLMANN, 1996, Abb. 7) is considerably more complicated than an earlier representation (NIGGLI and ZWART, 1973).

In the *upper level,* maximum temperatures, in mainly calcareous platform sediments (Permian to Jurassic), are of pre-orogenic origin and possibly linked to a diastathermal process (ROBINSON, 1987) in the crust of the Upper Austroalpine (FERREIRO MÄHLMANN, 1994). The degree of illite aggradation and rock maturity depends on the stratigraphic position. Illite-isocrysts and isoreflectance lines are subparallel to formation boundaries and are deformed in the same way. At the basal Silvretta thrust plane an important temperature discontinuity is demonstrated by IC, VR and index minerals (FERREIRO MÄHLMANN, 1995). In the *middle level* incipient metamorphism occurred during F1 and F2, dated on synkinematic white mica by the K–Ar method at 76–89 and 67–80 Ma, respectively (HANDY et al., 1996). In the Lower Austroalpine and Platta nappe geothermal gradients are not disturbed by F1 and F2 folding and faulting (FERREIRO MÄHLMANN, 1995), and thermal re-equilibration of Permian to Turonian rocks took place after nappe thrusting and during early Alpine metamorphism. However, areas of diagenetic grade are still preserved, indicating that the middle level never was deeply buried at the time of the Cretaceous and Tertiary Alpine orogeny. The northern part of the Lower Austroalpine and the northern Platta nappe never experienced pressures of more than 3 ± 1 kbar (FERREIRO MÄHLMANN, 1996). In the *lower level* metamorphism occurred after Tertiary D1 folding, and was effective during or before D2-deformation ("D1 to D3" analogous to SCHMID et al., 1990). Deformation after metamorphism, during D3 (WEH et al., 1996) modified the metamorphic zoning (e.g. the rock maturity pattern). The middle and lower level are separated by the Turba mylonite zone (NIEVERGELT et al., 1996), a conspicuous metamorphic discontinuity.

4.5.3 Upper Engadine and Malenco

In the Upper Engadine and Malenco, the boundary region between Central and Eastern Alps comprises from SW to NE, and from lower to higher tectonic level: the South-Penninic ophiolitic Forno unit (mainly mafic volcanic plus minor ultramafic rocks and their Mesozoic sedimentary cover), located south of the Engadine line and at the northeastern margin of the Bergell pluton; the Malenco unit (mainly serpentinized mantle-derived ultramafic rocks) with a preserved exhumed crust-mantle boundary; the Lower Austroalpine Margna nappe (basement and Permo-Mesozoic cover); the southern part of the Upper Penninic Platta nappe (Jurassic ophiolites and Lower and Middle Cretaceous sediments); and the Lower Austroalpine Err-Bernina nappe system (basement with Mesozoic cover).

Variscan meta-granitoids of the Bernina nappe contain Alpine neoformations of Ab, Act, Chl, Ep, Phe, Stp and Qtz (RAGETH, 1984). Variscan meta-granitoids of the Julier, Err, and Margna nappes, to the northwest of the Engadine Line, show the assemblage Qtz + Ab + Phe (3.4 Si p.f.u.) + Ep + Chl ± Stp ± Act (HANDY et al., 1996). Meta-radiolarites of the Platta nappe show the assemblage Qtz + Ab + Phe + Chl + Stp + Rbk + Act + Cal plus younger Agt + Grt (HANDY et al., 1996). In meta-granitoids of the Margna nappe southeast of the Engadine Line, chlorite in the NE is replaced by biotite in the SW (GUNTLI and LINIGER, 1989). In metabasites of the Margna nappe of the Malenco area, assemblages formed during D1 (nappe emplacement) and D2 (backthrusting) are Hbl + Act_1 + Ep + Olg + Ab + Qtz + Chl + Bt and Act_2 + Ep + Ab + Chl, respectively (BENNING and SIDLER, 1992). In the Malenco serpentinite the dominant regional metamorphic assemblage is Atg + Ol + Di + Chl + Mag, with Ti-rich clinohumite, brucite, Fe–Ni alloys, and sulfides as accessory phases (TROMMSDORFF and EVANS, 1972; BENNING and SIDLER, 1992).

Estimated peak metamorphic conditions for the upper Engadine range from 300–350 °C / 8–9 kbar for the base of the Err nappe to 450 °C / 6–9 kbar for the biotite zone of the Margna nappe (HANDY et al., 1996; Figs 3e and 3f). These pressure estimates are based exclusively on phengite barometry and may be too high (see below). Collectively, these data suggest HP greenschist facies conditions with a general trend of increasing metamorphic grade from NE to SW, i.e. with structural depth in the nappe pile. Further to the SE, in the Margna nappe, a synkinematic (D1) pressure maximum of 5 ± 1 kbar was derived from the crossite content of Ca-amphibole, followed by a postkinematic temperature maximum of 450 °C at lower pressure (BENNING and SIDLER, 1992). This orogenic metamorphism occurred during late Cretaceous time as discussed by HANDY et al. (1996).

5. Bergell area

The Bergell area, located in the transition from the Penninic units of the Lepontine area to the west and the Austroalpine units to the east and south, occupies a key position in the Alpine metamorphic history of the Central Alps (see e.g. SCHMID et al., 1996). The Tertiary Bergell granitoids mainly include tonalite (31.5 Ma), granodiorite (30 Ma) and the Novate granite (ca. 25 Ma), see GEBAUER, 1999, this volume, for a summary of radiometric ages. The Bergell pluton (tonalite and granodiorite) intruded synkinematically into the root zone of the Penninic and Austroalpine nappes (for details, see e.g. BERGER et al., 1996). Below the orogenic metamorphism in the western part of the Bergell area and the contact metamorphism of the Bergell pluton will be discussed separately. The regional greenschist facies metamorphism east of the Bergell pluton is of late Cretaceous age and was discussed in section 4.5.3.

5.1. OROGENIC METAMORPHISM IN THE WESTERN PART OF THE BERGELL AREA

The *Gruf complex* surfacing east of Val Mera and structurally below the floor of the Bergell pluton, represents the southeastern continuation of the Adula nappe. High-grade migmatitic quartzofeldspathic gneiss predominate over metapelitic schist and gneiss, amphibolite and calcsilicate marble. In metapelites, a common assemblage is Bt + Crd + Grt + Sil + Pl + Kfs + Qtz + Spl (WENK et al., 1974; BUCHER and DROOP, 1983). Whilst sillimanite is the dominant Al_2SiO_5 polymorph in Gruf metapelites, idiomorphic or hypidiomorphic kyanite is rarely seen together with fibrolite, but without direct reaction relationships (WENK et al., 1974). Two occurrences of sapphirine-bearing granulite have received special attention (DROOP and BUCHER, 1984 and references therein) and contain combinations of Grt, Opx, Spr, Sil, Crd, Bt, Qtz, Spl, Crn, St, Pl, Kfs, Ilm and Rt. Textural and mineral chemical data were used by DROOP and BUCHER (1984) to trace the evolution of the rocks in terms of successive equilibrium assemblages and to calculate P-T conditions pertaining to each stage. The inferred P-T history for the sapphirine-granulites can be summarized as follows: (i) increasing T at relatively high P (> 7 kbar), partial melting; (ii) a maximum T of 830 ± 70 °C attained at 10 ± 2 kbar; (iii) almost isothermal decompression, reaching 750 ± 100 °C at 5 ± 1 kbar. This P-T-t path was interpreted as the product of a single metamorphic cycle during Tertiary times. Migmatization is regarded to be contemporaneous with or slightly post-dating final emplacement of the Bergell pluton (BERGER et al., 1966).

The *Chiavenna ophiolite* (mainly ultramafic and mafic rocks, minor marble and calc-silicate) is found north of, and structurally above, the Adula-Gruf nappe, but beneath the structurally higher Tambo nappe. Mineral assemblages in ultramafic rocks (from antigorite-forsterite to enstatite-forsterite-spinel) indicate a marked increase of metamorphic grade towards the south, corresponding to an estimated metamorphic field gradient of 40–50 °C/km at 3.5–4 kbar (SCHMUTZ, 1976). This indicates the late-stage rapid exhumation of the high-grade Gruf unit along a subvertical tectonic contact situated between the Chiavenna ophiolite and the Gruf unit (BUCHER and DROOP, 1983).

5.2. CONTACT METAMORPHISM OF THE BERGELL PLUTON

An east-west profile across the tilted Bergell pluton exposes a 10 km-thick interval in terms of crustal depths. At the western contact of the pluton, the floor is exposed while the roof surfaces at the eastern contact (ROSENBERG et al., 1995; DAVIDSON et al., 1996). Geobarometry based on the Al content in hornblende indicates that the pressure of final crystallization of the Bergell tonalite decreases from 8.6 ± 0.3 kbar in the west to 4.3 ± 0.2 kbar in the northeast (DAVIDSON et al., 1996). This explains why a contact aureole of > 2 km in width developed in the east and none in the west.

Metamorphic isograds are well constrained in the Malenco serpentinite at the south-eastern margin of the Bergell intrusive (TROMMSDORFF and EVANS, 1972; TROMMSDORFF and CONNOLLY, 1996, and references therein). The following four isograds have been mapped, in order of increasing metamorphic grade: (i) the formation of tremolite and olivine (Tr-isograd, c. 1–2 km from the contact), at the expense of antigorite and diopside; (ii) the formation of talc and olivine (Tlc-isograd, c. 0.7–1.3 km from the contact), at the expense of antigorite; (iii) the formation of anthophyllite and olivine (Ath-isograd, c. 0.2–0.4 km from the contact); and (iv) the formation of enstatite and olivine (En-isograd, a few metres from the contact) at the expense of anthophyllite.

Two isograds have also been mapped within Mesozoic metapelites of the Forno unit at the north-eastern margin of the Bergell pluton (TROMMSDORFF and NIEVERGELT, 1983), i.e. an andalusite and a sillimanite isograd (c. 2 and 0.5 km from the contact, respectively).

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