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# Alpine metamorphism along the Geotraverse Basel–Chiasso – a review

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ABSTRACT

The mineralogical zonation, the geothermometry and geobarometry as well as some aspects of the timing of the Alpine metamorphism along the Swiss Geotraverse are reviewed. In addition, a new zonation of metamorphism based on fluid inclusions from fissure quartz crystals is presented.

ZUSAMMENFASSUNG

Die mineralogische Zonierung, Temperatur- und Druckabschätzungen sowie einige Gesichtspunkte zur Datierung der alpinen Metamorphose entlang der Schweizerischen Geotraverse werden besprochen. Zusätzlich wird eine neue Zonierung der Metamorphose mit Hilfe von Gas- und Flüssigkeitseinschlüssen in Kluftquarzen vorgestellt.

## 1. Introduction

During the last twenty years a lot of information about the Alpine regional metamorphism of the Central Alps has been assembled, and reviews have been presented by NIGGLI (1970), WENK (1970), ERNST (1973) and FREY et al. (1974). The knowledge of Alpine and pre-Alpine metamorphism along the Geotraverse Basel–Chiasso was summarized by FREY et al. (1976). Since that time research has been focused on the following topics:

— Diagenesis and very low-grade metamorphism in the Helvetic Alps (FREY 1978; FREY et al. 1980; BREITSCHMID 1980) and the Southern Alps (DUNOYER & BERNOULLI 1976).

— Alpine petrology of pre-Triassic metapelites of lower Pennine nappes (KLEIN 1976*a, b;* STAPS, in prep.; KOCH, in prep.).

— Petrology of ultramafic and mafic rocks on a regional scale, especially of the Cima Lunga zone (EVANS & TROMMSDORFF 1978; ERNST 1978; EVANS et al. 1979; PFEIFER 1978, 1979).

— Petrofabric studies dealing with the relationships between Alpine crystallization and deformation (MILNES 1976; VOLL 1976; VOGLER & VOLL 1976; ROSENFELD 1978; HUBER et al. 1980).

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- Detailed local petrographical studies (IROUSCHEK 1978; HEINRICH 1978; STÄUBLE 1978; ZINGG 1979; SCHLÄPFER 1979; BÜHL 1980; KLAPER 1980).
- Feldspar mineralogy (related to Alpine metamorphism) (STECK 1976; HISS 1978; LOIDA 1978; WENK & WENK 1977; WENK 1979; BERNOTAT & BAMBAUER 1980).
- Radiometric dating of metamorphic and tectonic(?) phases and subsequent cooling history (SCHAER et al. 1975; PURDY & JÄGER 1976; WAGNER et al. 1977; KÖPPEL & GRÜNENFELDER 1975, 1978; STEIGER & BUCHER 1978; HUNZIKER 1979).
- Stable isotope work related to Alpine geothermometry and degree of fluid migration during Alpine and pre-Alpine time (HOERNES & FRIEDRICHSEN 1980).
- Fluid inclusion studies (MERCOLLI 1979; MULLIS 1979).

The above mentioned studies have added little to our knowledge of the pre-Alpine metamorphism (exceptions: HOERNES & FRIEDRICHSEN 1980, possibly also EVANS et al. 1979). Therefore, only the Alpine metamorphic history will be dealt with here and the following topics will be reviewed: mineralogical zonation, geothermometry/geobarometry and timing of Alpine metamorphism. In addition, some new results on fluid inclusions and their relation to the metamorphic zonation will be presented.

Since many of the studies to be reviewed in the following were performed along the Gotthard railway, we have chosen a 30–50 km wide strip limited in the west by the transect line Basel–Chiasso and in the east by the Glarus Alps, Lukmanier pass and Valle Mesolcina (Fig. 2).

Metamorphic grade will be designated by the terms non-, anchi-, epi- and meso-metamorphic. Some of these terms have long been used in Alpine petrology. Here they are used in a descriptive sense and do not imply that the essential controlling factor is depth as they did when first introduced (GRUBENMANN 1904).

## 2. Mineralogical zonation

A regular (and systematic) distribution pattern of metamorphic minerals and mineral assemblages can be recognized along the Geotraverse. This regular large-scale pattern may be related to a systematic increase of metamorphic grade (i.e. mainly temperature) from the north to the south. However, recent petrological studies along the Geotraverse (and elsewhere in the Central Alps) have shown that the apparently simple overall picture of the Alpine metamorphism might be the result of a complicated metamorphic history (see below).

Figure 1 relates the appearance or disappearance of some important minerals from different bulk rock compositions to metamorphic grade. It should be noted that most of these so called isograds represent mineral zone boundaries and cannot be related to a reaction-isograd (WINKLER 1979, p. 66). Mapping of reaction-isograds is impeded by a number of reasons:

- Lack of continuous outcrops for a specific bulk rock composition (particularly for ultramafic, pelitic and dolomitic compositions).

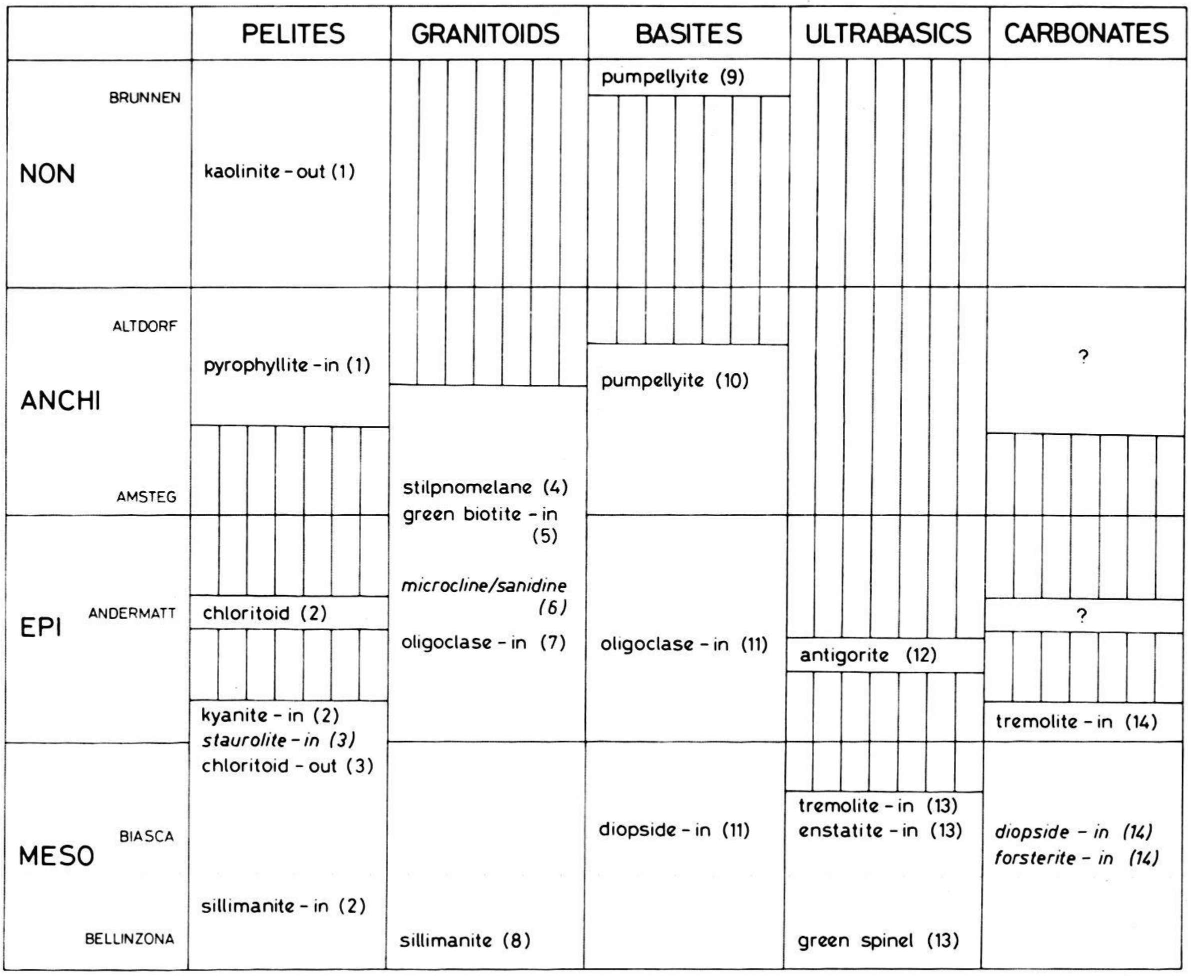


Fig. 1. Appearance, disappearance or local presence of some diagnostic minerals in different lithologies along the Geotraverse. Reaction-isograds are shown in italics. The ruled pattern indicates areas where rocks of the specific lithology are lacking.
(1) Breitschmid (1980); (2) Niggli & Niggli (1965); (3) Niggli & Niggli (1965), Fox (1975); (4) Niggli & Niggli (1965), Jenni (1973); (5) Steck & Burri (1971), Jenni (1973); (6) Bernotat & Bambauer (1980); (7) Steck (1976); (8) Fumasoli (1974); (9) Dietrich et al. (1974); (10) Martini & Vuagnat (1965), Stalder (1979), Kisch (1980); (11) Wenk & Keller (1969); (12) Ambühl (1929); (13) Trommsdorff & Evans (1974); (14) Trommsdorff (1966).

- Critical mineral assemblages are often missing due to unfavourable bulk rock compositions.
- Local fluctuations in fluid composition may lead to an apparent inversion of increase in metamorphic grade (e.g. in ultramafic rocks high-grade assemblages may be present in a $CO_2$-rich environment in the north, whereas low-grade assemblages still can be found in a $H_2O$-rich environment in the south).
- Petrographic observations in thin sections indicate a complex metamorphic history of the area even for the monometamorphic (but possibly plurifacial) Mesozoic and Cenozoic rocks. Based on textural evidence the mineral content of a specific rock can in many cases be associated with several assemblages reflecting different metamorphic stages.

To illustrate some problems encountered in studying the Alpine metamorphism, different bulk rock compositions are briefly discussed in turn below.

### *a) Pelites*

Kaolinite-out and pyrophyllite-in mineral zone boundaries, separated by about 10 km, have been mapped in the higher Helvetic nappes and the autochthonous cover of the Aar Massif, respectively (BREITSCHMID 1980). Due to unfavourable bulk rock composition the reaction isograd kaolinite + quartz → pyrophyllite + $H_2O$ could not be located.

The beginning of the anchizone is based on illite crystallinity data (BREITSCHMID 1980). Note the curved boundary west of Altdorf (Fig. 2), which is an effect of transported metamorphism.

The next metapelites to the south crop out in the Urseren zone. Abundant chloritoid (as well as margarite) can be found in Mesozoic and sporadically, also in Carboniferous metasediments (AMBÜHL 1929; NIGGLI & NIGGLI 1965) but pyrophyllite is absent. Reaction-isograds leading to these mineralogical changes are hidden somewhere in the Aar Massif further to the north (cf. FREY & WIELAND 1975).

Kyanite is found in places in the Tremola series at the southern border of the Gotthard Massif (NIGGLI & NIGGLI 1965) but is abundant in lower Liassic metapelites of the Lukmanier area (FOX 1975). A reaction-isograd responsible for this mineralogical change has not yet been defined.

The characteristic low-grade assemblage in the lower Liassic of the northern Lukmanier area is chloritoid + chlorite + kyanite (together with muscovite + quartz). Further to the south, within a distance of only 2 km, these metapelites define three reaction-isograds leading first to the appearance of staurolite (chloritoid + kyanite → staurolite + chlorite + quartz + $H_2O$), then biotite (chloritoid + chlorite + muscovite → biotite + staurolite + quartz + $H_2O$) and finally garnet (choritoid + muscovite + quartz → garnet + staurolite + biotite + $H_2O$). Note that these are the only reaction-isograds in metapelites mapped along the Geotraverse so far. At higher metamorphic grade, the *AFM* four-phase assemblage biotite + staurolite + kyanite + garnet, accompanied by fibrolitic sillimanite in the south, persists over the whole Lepontine area except for a small strip in the Bellinzona zone (FUMASOLI 1974; BÜHL 1980). Here, the above mentioned assemblage is replaced by biotite + sillimanite + garnet. In the Tonale series along the Insubric Line, on the other hand, staurolite appears again in metapelitic gneisses (staurolite + biotite + garnet + rare sillimanite, FUMASOLI 1974; p. 120). This indicates lower metamorphic conditions for the Tonale series as compared with the Bellinzona zone, a conclusion also supported by the marble assemblage dolomite + calcite + quartz + talc (FUMASOLI 1974), although part of the mineral assemblages near the Insubric Line may be of retrograde origin. The age of the metamorphic mineral assemblages in the Tonale series is still problematic, as sillimanite occurs also far in the east, e.g. between Tirano and Tonale pass, where the grade of Alpine metamorphism is low.

Prograde chlorite has been reported from Mg-rich bulk compositions (together with cordierite + kyanite + quartz) from the Verzasca valley (WENK 1968).

Overgrowth of possible sillimanite needles on partly prekinematic kyanite has been described from the Pizzo Forno-Campo Tencia area (ADAMS et al. 1975, p. 597; IROUSCHEK 1978) and the Lukmanier area (ADAMS et al. 1975, p. 596), that is up to 30 km north of the former sillimanite "isograd". Transmission electron microscopic results are needed to substantiate these optical data. In the high-grade zone of the Lepontine area sillimanite presumably formed in part by continuous reactions (e.g. garnet + K-feldspar + $H_2O$ → biotite + sillimanite + quartz, BÜHL 1980) and its appearance cannot be related to a reaction-isograd caused by a discontinuous reaction such as muscovite + quartz → sillimanite + K-feldspar + $H_2O$.

The metapelites of the central Lepontine area portray a complex metamorphic history. Detailed petrographic studies have shown that most minerals are present in different generations based on textural and chemical evidence. As an example three garnet, three kyanite and two biotite generations have been observed at Cima di Gagnone (SCHLÄPFER 1979). The Lepontine area suffered at least three main phases of deformation (e.g. HUBER et al. 1980) and the observed minerals apparently grew before, during and after the two later phases of deformation (AYRTON & RAMSAY 1974). Therefore, in the light of recent petrographic and structural observations as well as isotopic data (see below) the frequently used term "the peak of the Lepontine phase of metamorphism" appears somewhat dubious.

The retrograde branch of the metamorphic history is, for example, documented by overgrowth of paragonite on bent kyanite crystals at Gagnone (STÄUBLE 1978).

Of particular interest are the widespread aluminium silicate nodules which show the succession kyanite → andalusite → sillimanite → muscovite + chlorite (KELLER 1968; WENK 1970; KLEIN 1976*b*; HEINRICH 1978; CODONI, in prep.). This observed sequence probably documents an uplift history with initially increasing temperature prior to cooling.

### *b) Granitoids*

The lowest-grade Alpine metamorphic minerals recorded are prehnite (a single occurrence as an alteration product of biotite near Erstfeld, VOLL 1976, p. 641), stilpnomelane, Ca-Mn-Fe-garnet and epidote (JENNI 1973), and green biotite (STECK & BURRI 1971; JENNI 1973). However, stilpnomelane has been reported from iron-rich metasediments and glauconitic limestones north of the Aar Massif (NIGGLI & NIGGLI 1965; BREITSCHMID 1980) and the green biotite-in and stilpnomelane-out mineral zone boundaries have not been documented in detail so far.

A special kind of mineralogical zonation has been worked out by VOLL (1976), who studied the polygonization, strain-induced grain boundary migration and recrystallization in response to Alpine deformation of quartz, biotite and feldspars in the Aar and Gotthard Massifs as well as in the Leventina gneiss. Between Amsteg and Airolo, the volume of recrystallized quartz grains steadily increases and it may be possible to map correspondingly three-dimensional boundary curves (G. Voll, pers. comm. 1978). According to VOLL (1976, p. 645) the onset of recrystallization in the Gotthard Massif and the lower Penninic nappes south of it has important consequences for the tectonic style of this area: plastic deformation in the south versus rigid behaviour in the north.

In granitoid rocks of the southern Aar Massif, a microcline-sanidine transformation-boundary can be mapped (BERNOTAT & BAMBAUER 1980) which is based on careful X-ray studies of alkali feldspars. As pointed out by these authors, the Al-Si-distribution state observed today was frozen in during the cooling history and not during the climax of metamorphism. The incoming of oligoclase in the Gotthard Massif describes a relatively well-defined mineral zone boundary caused by the peristerite gap (STECK 1976).

In the Lepontine area granitoid rocks almost uniformly contain quartz + K-feldspar + plagioclase + biotite ± muscovite ± garnet. Feldspars have responded to retrograde effects as will be described on page 538 (HISS 1978). An exception is found in the Bellinzona zone where sillimanite joins the above mentioned assemblage (FUMASOLI 1974, p. 130).

### *c) Basites*

Pumpellyite together with chlorite + albite + quartz has been reported from metavolcanics of the Iberg Klippen (DIETRICH et al. 1974, p. 304, 325). It is not known whether these rocks suffered an oceanic metamorphism or represent a case of transported regional metamorphism (note that the underlying sediments belong to the nonmetamorphic zone).

The Taveyannaz sandstone formation - greywackes of Eocene-Oligocene age - of the Altdorf-Schächental area contain pumpellyte + prehnite + epidote + chlorite + albite + quartz (MARTINI & VUAGNAT 1965; STALDER 1979; KISCH 1980).

Data on Alpine assemblages from polymetamorphic mafic rocks of the Aar Massif are hardly available and do not allow for further distinction of mineral zones along the Geotraverse. Typical epimetamorphic assemblages (biotite + chlorite + actinolite + muscovite + albite + quartz, or biotite + chlorite + epidote + muscovite + albite + quartz) occur in Permo-Carboniferous metavolcanics of the Urseren zone (AMBÜHL 1929) and polymetamorphic mafic rocks of the northern Gotthard Massif (ARNOLD 1970).

In the Lepontine area metabasites are represented by amphibolites, eclogites and metarodingites. In amphibolites the appearance of diopsidic clinopyroxene has been documented by WENK & KELLER (1969), but details of this specific mineral zone boundary as well as general phase relations of mafic schists and gneisses await to be unraveled. Metabasites of the Adula nappe and Cima Lunga zone still bear the imprint of an earlier eclogite facies metamorphism of pre-Alpine or early Alpine age (see p. 540) which survived the mesozonal Tertiary overprint (EVANS et al. 1979). Garnet + omphacite + kyanite are typical assemblages of the eclogites at Arami and Gagnone, whereas garnet + clinopyroxene characterize metarodingites.

The mineral sequence chlorite → prehnite → laumontite documents the retrograde branch of the Lepontine mesozonal metamorphism (IROUSCHEK 1978, p. 46).

### *d) Ultrabasics*

The most northerly metaperidotites along the Geotraverse are found in the northern Gotthard Massif. The mineral pair antigorite + talc is common (AMBÜHL

1929). Metasomatic silica enrichment led to unfavourable bulk compositions and therefore other diagnostic mineral assemblages are absent.

The scarcity of ultramafic rocks in the Lepontine area renders mapping of reaction-isograds impossible. The mineral pair tremolite + forsterite is found throughout this area along the Geotraverse. Ultramafic rocks of the upper Maggia valley and in the northern part of the Cima Lunga zone contain magnesian amphiboles (anthophyllite and/or cummingtonite) and magnesite. The first appearance of the mineral pair enstatite + forsterite marks a mineral zone boundary in magnesite-bearing ultramafic rocks (TROMMSDORFF & EVANS 1974). In carbonate-free rocks, however, lower grade assemblages such as anthophyllite + forsterite or talc + forsterite persist further to the south. At Loderio near Biasca, for example, enstatite + forsterite + magnesite and talc + forsterite can be found at the same outcrop. These observations can be explained by significant local fluctuations in the composition of the metamorphic fluid, which seems to be a typical phenomenon of the Lepontine area (EVANS & TROMMSDORFF 1970; TROMMSDORFF & EVANS 1974; PFEIFER 1978, 1979). The distribution of ultramafic assemblages implies recrystallization under partly high $CO_2$-pressures. The occurrence of green spinel in the Bellinzona zone could be due to such high $CO_2$-pressures.

Analogous to the mafic rocks, a high-pressure metamorphism of early Alpine or of pre-Alpine age can be demonstrated for several garnet-peridotites of the Lepontine area (EVANS & TROMMSDORFF 1978; MÖCKEL 1969; FUMASOLI 1974). The reported occurrences of the mineral pair diopside + forsterite in ultramafics probably also belongs to this event.

Recent petrologic studies have revealed an amazingly complex metamorphic history for ultramafic rocks (EVANS & TROMMSDORFF 1978; EVANS et al. 1979; FUMASOLI 1974; HEINRICH 1978; STÄUBLE 1978; PFEIFER 1979). This complexity is not restricted to polymetamorphic rocks (eclogites, garnet-peridotites); also the Tertiary metamorphic phase may be subdivided into a number of successive periods of mineral growth and deformation.

### *e) Carbonates*

No data are available for the low-grade section of the Geotraverse (Helvetic Alps, Urseren zone). South of the Gotthard Massif *dolomitic marbles* contain tremolite (TROMMSDORFF 1966). Two reaction-isograds lead to the appearance of diopside (tremolite + calcite + quartz → diopside + $H_2O$ + $CO_2$ and tremolite + calcite → diopside + dolomite + $H_2O$ + $CO_2$) and forsterite (tremolite + dolomite → forsterite + calcite + $H_2O$ + $CO_2$ and diopside + dolomite → forsterite + calcite + $CO_2$). Their relative sequence in a N-S profile is not clear due to the rare occurrence of an adequate rock composition, the presence of more than one active mineral reaction and the nature of the mixed-volatile reactions. At a large scale, the two above mentioned reaction-isograds coincide, and furthermore they also approximately coincide with the diopside mineral zone boundary for mafic rocks and with the enstatite mineral zone boundary for ultramafic compositions.

The low-grade assemblages tremolite + dolomite and tremolite + calcite + quartz, diopside + dolomite have been reported throughout the diopside and forsterite zone, respectively. This observation may be explained by several phases of Alpine metamorphism, or by an externally controlled fluid composition of relatively high $X_{CO_2}$ and/or by extensive solid-solution of extra components into the tremolitic amphibole.

A retrograde formation of tremolite within the diopside zone according to the reaction diopside + $H_2O$ + $CO_2$ → tremolite + calcite + quartz has also been observed. Detailed studies of the Campolungo dolomites by MERCOLLI (1979) showed that the complex metamorphic history observed in other rock compositions can be demonstrated for siliceous dolomites as well. Particularly the formation of talc in the Campolungo dolomites appears to be connected with the uplift and cooling branch of the metamorphic evolution.

Calcschists and carbonate-mica-schists ("Bündnerschiefer") cover a wide range of bulk composition and hence contain a bewildering variety of mineral assemblages within the Pennine realm. No systematic regional study on the petrology of the Bündnerschiefer is available at present along the Geotraverse, although some important progress has been achieved in the Simplon-Verampio area (FRANK 1979).

The only located mineral zone boundary in the Bündnerschiefer along the Geotraverse refers to the appearance of diopside, which is found approximately at the same metamorphic grade as in siliceous metadolomites. Recent local petrographic studies on Bündnerschiefer from the Gagnone area (SCHLÄPFER 1979; ZINGG 1979) and the upper Maggia valley (KLAPER 1980) detected a complex sequence of mineral growth and rock deformation. Mineral assemblages of both the prograde and retrograde branch of metamorphism may be detected in one thin section. The maximum phase content of a Bündnerschiefer from Gagnone, for example, is tremolite-diopside-epidote-plagioclase-scapolite-biotite-garnet-quartz-calcite-sphene. Textural observations indicate that tremolite formed retrograde from diopside, scapolite formed from zoisite and decomposed to plagioclase + calcite, while garnet (together with plagioclase) presumably formed from zoisite + quartz and decomposed to plagioclase + calcite + quartz. These rocks obviously never attained chemical equilibrium, a fact which could be responsible for the large variation of plagioclase composition (cf. FREY 1974, p. 502).

## 3. Fluid inclusions and metamorphic zonation

Fluid inclusions from fissure quartz crystals of 40 localities between the Alpine border zone and Bellinzona were studied by microthermometry and Raman spectroscopy. The fluid composition of early generations of fluid inclusions shows a regular zonation, remarkably closely related to Alpine metamorphic grade (MULLIS 1979, see Figure 2 and the Table).

It is believed that the early fluid inclusions reflect a fluid evolution during the prograde Alpine metamorphism while later inclusions are related to the retrograde path of metamorphism (MULLIS, in prep.). However, it cannot be generally assumed that the fluids of the early inclusions correspond to the fluid composition during the peak of metamorphism. This seems to be especially true for the epi- and mesozone, where already the early fluid inclusions show a fluid composition influenced by small retrograde changes. On the other hand, the early inclusions from the nonmeta-

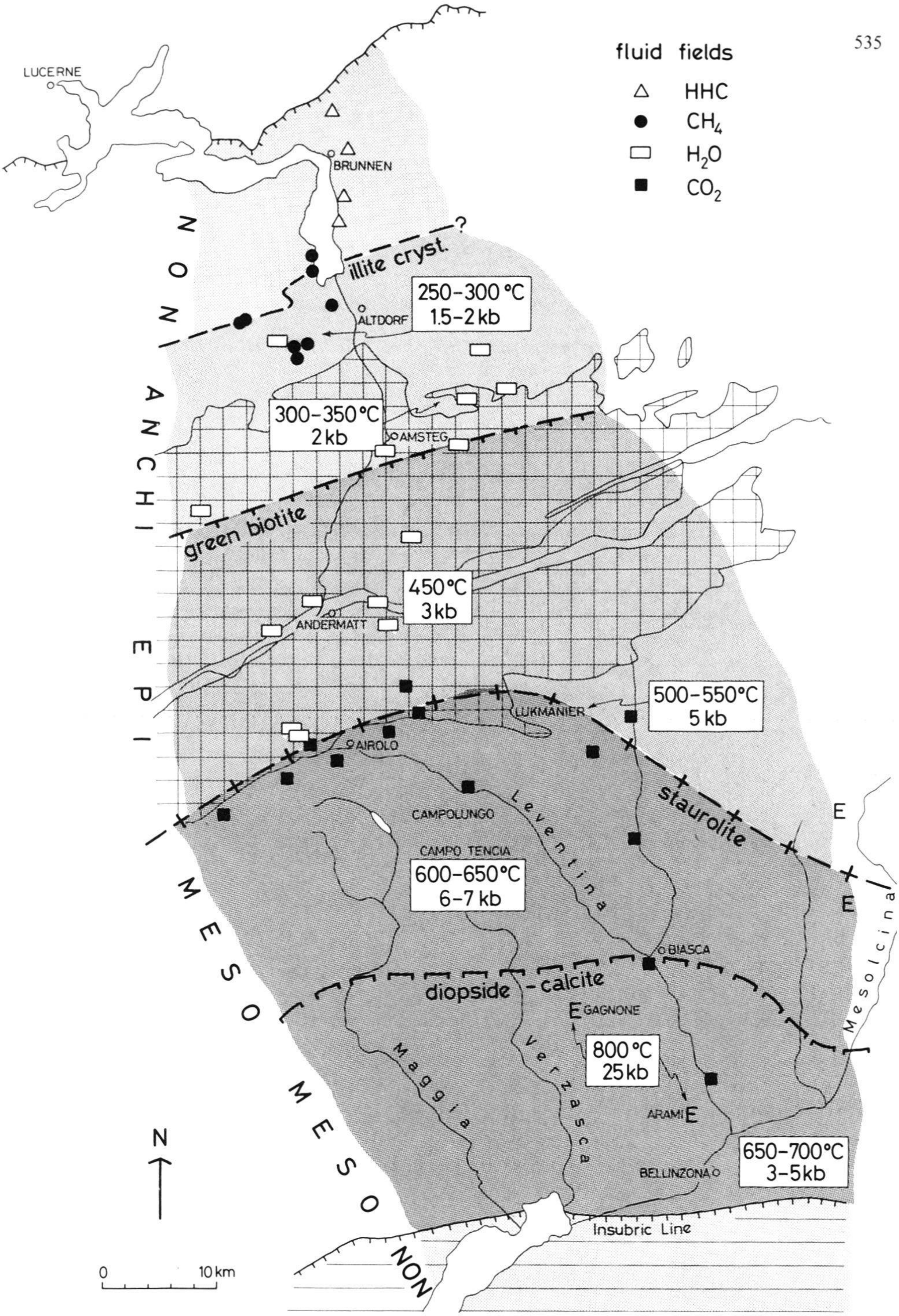


Fig. 2. Alpine metamorphic map along the Geotraverse. *E* = eclogites of the Adula nappe and Cima Lunga zone. Pressure/temperature estimates are discussed in the text. The *P/T* values of Arami-Gagnone refer to early Alpine or pre-Alpine metamorphism, all other estimates refer to Tertiary Alpine metamorphism. The fluid composition from fissure quartz crystals is also indicated.

Table: *Fluid fields, fluid composition and metamorphic grade of earliest fluid inclusions.*

| fluid field | fluid composition | metamorphic grade |
|---|---|---|
| HHC* | ~1 to >80 mole-% HHC<br>($CH_4$, $H_2O$, $CO_2$, NaCl)** | non-metamorphic zone |
| $CH_4$ | ~1 to >90 mole-% $CH_4$,<br><1 mole-% HHC<br>($H_2O$, $CO_2$, NaCl) | low- and medium-grade anchizone |
| $H_2O$ | ~90 to >99 mole-% $H_2O$,<br><1 mole-% $CH_4$<br>($CO_2$, NaCl) | high-grade anchizone and epizone |
| $CO_2$ | ~10 to >60 mole-% $CO_2$<br>($CH_4$, $H_2O$, NaCl) | mesozone |

* HHC = higher hydrocarbons

** in brackets: additional species found in inclusions. Furthermore, small amounts (<3 mole-%) of $H_2S$ and $N_2$ may be present as well.

morphic zone and the anchizone show a fluid composition which was presumably almost identical with the fluid composition during the peak of metamorphism.

## *Origin of fluids in metasediments*

The higher hydrocarbons in fluid inclusions from the nonmetamorphic zone were derived from organic material through biochemical and geochemical processes during the sedimentary burial.

The predominance of $CH_4$ in the low- and medium-grade anchizone is due to the cracking of the higher hydrocarbons with an increase in temperature and pressure. In the higher grade anchizone and in the epizone, $H_2O$ is the dominant fluid species. The transition from methane to water is probably controlled by the presence of graphite under conditions near the quartz-fayalite-magnetite (*QFM*) buffer. As shown by EUGSTER & SKIPPEN (1967), a C-O-H fluid, in the presence of graphite, the *QFM* buffer and at a pressure of 2 kbar, is mainly composed of methane at 300 °C, whereas water is predominant at 450 °C. Under relatively oxidizing conditions near the nickel-bunsenite buffer $CH_4$ is expected to convert to $CO_2$ and $H_2O$. The $CO_2$ was probably fixed in carbonates.

The mesozone is characterized by a mean $CO_2$ content of 10-60 mole-% in the fluid phase. This $CO_2$ may have been originated through decarbonation reactions and the oxidation of graphite. In addition, some juvenile $CO_2$ may be present, although this question has not been definitely answered (HOEFS & STALDER 1977).

*Origin of fluids in granites and gneisses*

The fluid composition of granites and gneisses from the Aar and Gotthard Massifs were less influenced by the epizonal Alpine metamorphism than those of the metasediments. Some influence during the retrograde metamorphism can be ascertained by trace element analysis, e.g. a decrease of the K/Na-ratio in fluid inclusions (POTY et al. 1974; MULLIS, in prep.).

The fluid inclusions from quartz crystals of the Leventina orthogneiss show smaller amounts of $CO_2$ than those of the northern Penninic Bündnerschiefer. Since carbonates and graphite are missing in this gneiss, the $CO_2$ may possibly be of juvenile origin.

## 4. Geothermometry, geobarometry and geothermal gradients

Although some progress has been made in this field since the last report (FREY et al. 1976), the present state of knowledge is still unsatisfactory due to the following reasons:

- Determinations of temperature and pressure are often charged with an error in the order of 50 °C and up to several kilobars.
- $P$ and $T$ values derived from mineral equilibria involving a fluid phase are dependent on the activity of the fluid species. Temperature estimates based on dehydration reactions, e.g. with the commonly made assumption of $P_{H_2O} = P_{total}$, are presumably often too high in the light of high $CO_2$ contents found in granitoid gneisses (see above) and metapelites of the Lepontine area (J. Mullis, unpublished results). However, direct determinations of the fluid composition during metamorphism are only rarely available.
- Independently determined (maximum?) values of $P$ and $T$ do not necessarily correspond to the same period of time. In the model advocated by ENGLAND & RICHARDSON (1977), for example, the maximum pressure is reached earlier than the climax temperature.

In the following section $P/T$ estimates are discussed from north to south and some of these values are portrayed in Figure 2.

The most reliable data from the Helvetic nappe zone are based on fluid inclusion studies from fissure quartzes (MULLIS 1979; FREY et al. 1980). From five localities of the low-grade anchimetamorphic North-Helvetic Flysch zone (to the west of Altdorf) the following $P$ and $T$ values were obtained: 1780 bar (range: 1310-2490 bar) and 258 °C (range: 250-264 °C). Although these data represent minimum values they are believed to be near the conditions which prevailed during the regional metamorphism (MULLIS 1979, p. 535). From the reflectivity of finely dispersed organic material in the Taveyannaz sandstone east of Altdorf, STALDER (1979) derived a temperature of about 260 °C. In Figure 2 we have therefore given the preference to 250–300 °C/1.5–2 kbar.

For the Windgällen area (northern rim of the Aar Massif) a pressure of 2.1 ± 0.7 kbar was determined with aid of the sphalerite geobarometer (SCHENKER 1980). Based on the salt content of fluid inclusions from a quartz vein and the above mentioned pressure value a temperature range of 305–430 °C was obtained. From a regional context the lower temperature limit seems to be more reasonable. Therefore, *P/T* values of 300–350 °C/2 kbar are indicated in Figure 2.

Insufficient data are available for the southern Aar Massif and the Urseren zone. Temperature values are from three different sources. Oxygen isotope temperatures of 460–530 °C were obtained for three quartz-biotite pairs and one quartz-magnetite pair from Göschenen and Andermatt (HOERNES & FRIEDRICHSEN 1980). For the microcline-sanidine inversion boundary which is located between Göschenen and Andermatt, a temperature of 450 °C was suggested by BERNOTAT & BAMBAUER (1980). Temperatures calculated from K/Na ratios of fluid inclusions yielded an average value of 430 °C for the central zone of the Aar Massif (POTY et al. 1974, Table V). The temperature of 450 °C indicated in Figure 2 may be rather low, while the pressure of 3 kbar represents the rounded-off value of the 2.8 kbar derived from fluid inclusion studies from Alpine fissure quartzes of the southern Aar Massif (POTY et al. 1974).

The *P/T*-estimate for the Lukmanier area (500–550 °C/5 kbar) is based on phase equilibrium studies of rock-forming silicate, carbonate and oxyde minerals (presence of chloritoid + staurolite + kyanite + quartz, and margarite + staurolite + quartz, several geothermometers such as muscovite-paragonite, calcite-dolomite and magnetite-ilmenite) and on the investigation of piezobirefringent halos of quartz inclusions in garnet (FOX 1974; 1975; ADAMS et al. 1975; FREY 1978).

Some stage during the retrograde metamorphic path was recorded in metadolomites from Campolungo (MERCOLLI 1979). A temperature of around 500 °C was derived from calcite-dolomite thermometry while the estimated pressure of 1.5 kbar depends on the cooling model of WERNER et al. (1976) and is probably too low. Note, that HOERNES & FRIEDRICHSEN (1980) suggest an oxygen isotope temperature of about 630 °C for the Campolungo area, although calculated temperatures cover a large range between 500 and 680 °C.

Another example of low temperature recording in the mesozone comes from granitoid gneisses of the Lepontine area. For the Leventina gneiss, e.g., two-feldspar thermometry yielded a temperature of only around 400 °C, and this may represent "a sort of structurally defined blocking temperature" after the climax of metamorphism (HISS 1978). Using homogenized alkalifeldspar, however, temperatures between 500 and 650 °C were obtained, and these values are consistent with other maximum temperature estimates of the area.

For the Campo Tencia–Pizzo Forno area a *P/T* estimate of 600–650 °C/6–7 kbar is shown in Figure 2. These data are based on the occurrence of the assemblage muscovite + paragonite + sillimanite (IROUSCHEK 1978), oxygen isotope thermometry (HOERNES & FRIEDRICHSEN 1980) and stress effects around quartz inclusions in garnet (ROSENFELD 1969; ADAMS et al. 1975).

Completely different $P/T$ values of $800 \pm 50$ °C and $25 \pm 5$ kbar are recorded for garnet lherzolites, eclogites and metarodingites of two localities (Gagnone, Arami) of the Adula nappe and Cima Lunga zone (EVANS & TROMMSDORFF 1978; EVANS et al. 1979). These $P/T$ data were derived from element partitioning between garnet, orthopyroxene, clinopyroxene and olivine. As noted by these authors, such high $P$ and $T$ values must be attributed to an early Alpine or pre-Alpine metamorphism, because metapelitic gneisses and metacarbonate rocks at Gagnone record $P/T$ conditions compatible with the Tertiary metamorphism of the Lepontine area. A direct emplacement of the garnet lherzolites from the mantle into their present position seems unlikely as discussed by EVANS & TROMMSDORFF (1978, p. 345).

The $P/T$ estimate for the Bellinzona zone (650–700 °C/3–5 kbar) is not well documented. HEITZMANN (1975), working about 20 km to the east of Bellinzona, suggested 670–700 °C/3.5–5 kbar for metapelitic and granitoid gneisses (incipient anatexis, alkalifeldspar + sillimanite). The possible presence of $CO_2$ (see p. 537) has not been considered in the above mentioned estimates.

Summarizing the data presented above, it can be said that, apart from the exceptionally high $P/T$ conditions found for some rocks of the Adula nappe and Cima Lunga zone and some clear effects of retrograde overprinting, the estimated $P/T$ values display a fairly regular increase from Lake Lucerne to the southern Lepontine area. Only the Tonale Series, located directly north of the Insubric Line, indicates a decrease in metamorphic grade (see p. 530). It should be noted that no obvious break in Alpine metamorphic grade along the Geotraverse could be detected, although the metamorphism of the Helvetic and Pennine zones may not be of the same age.

Mean *geothermal gradients* calculated from $P/T$ values and reasonably assumed rock densities ($d = 2.7$–$2.9$ g/cm$^3$) appear to decrease from the north to the south as noted earlier by FREY et al. (1976) and FREY (1978, p. 132). Values calculated in this study are as follows: Altdorf $\approx 40$ °C/km (range: 33–53 °C/km); Andermatt $\approx 40$ °C/km; Lukmanier area $\approx 25$–30 °C/km; Campo Tencia-Pizzo Forno area $\approx 25$–30 °C/km (range: 23–31 °C/km). From these data FREY et al. (1976, p. 653) concluded that isotherms were presumably gently inclined to the south during the climax of metamorphism. This conclusion deserves several comments.

- A pair of $P$ and $T$ values used for the calculation of a mean geothermal gradient does not necessarily belong to the same point of time (ENGLAND & RICHARDSON 1977).
- The Tertiary regional metamorphism along the Geotraverse may have been younger in the north than in the south.
- The lower mean geothermal gradients in the south have been derived from deeper crustal levels ($\sim$18–25 km) than in the north ($\sim$5–11 km). Since it is well-known that the geothermal gradient decreases with increasing depth, our observed different values may be solely the result of different crustal levels exposed at the earth surface today (P. Thompson, pers. comm.).

At the present state of knowledge there seems to be no evidence which would argue against a subhorizontal position of isotherms during the climax of metamorphism. As pointed out by FREY et al. (1976, p. 653), this result conflicts with recently described reaction-isograd surfaces which show a minimum dip of 35° towards the north for the Lukmanier area (FOX 1975) and a 50–70° northerly dip for the Mesolcina valley (THOMPSON 1976). Since these reaction-isograds are based on dehydration reactions, they presumably do represent isotherms. FREY et al. (1976) had no plausible explanation for this dilemma but subsequent discussions with A.G. Milnes offered a possible explanation as discussed below. Combined structural and textural evidence has shown that very large-scale folding was going on *during* the Tertiary metamorphism in the Lepontine gneiss region (e.g. Wandfluhhorn: MILNES 1974) and in adjacent areas (e.g. Suretta: MILNES & SCHMUTZ 1978). It is now generally agreed that heat flow cannot keep pace with thrusting or folding. Thus, there was probably large-scale overfolding of originally subhorizontal isotherms which later only partly reestablished their former position (see also MILNES 1975).

## 5. Timing of metamorphism

It is now well established that there exist at least two phases of Alpine metamorphism in the Alps, which are of late Cretaceous (Eo-Alpine or early Alpine metamorphism) and mid-Tertiary (meso-Alpine and neo-Alpine) age (e.g. FREY et al. 1974; TRÜMPY 1980). The regional metamorphism which is responsible for the systematic metamorphic zonation of the Lepontine area is of mid- to late Tertiary age. There remain three open questions concerning the timing of metamorphism along the Geotraverse:

a) Existence of an early Alpine metamorphism.

b) Precise dating of the Tertiary metamorphism and its possibly complex evolution.

c) Time relationship between the low-grade metamorphism of the Helvetic nappes and the Aar Massif to the metamorphism in the Lepontine area.

ERNST (1973) suggested that the lower Pennine nappes of the Lepontine Alps underwent an early Alpine high pressure-low temperature metamorphism, although the available evidence is not conclusive at all. Certainly, the mesometamorphic overprint by the Lepontine metamorphism makes it difficult to detect remnants of the earlier history. The high-pressure rocks of the Adula nappe and Cima Lunga zone represent possible candidates for such early Alpine remnants, but they could also be of pre-Alpine age. The fresh appearance of these rocks is in favour of an early Alpine metamorphic origin because of the following reasoning. Pre-Alpine high-pressure metamorphic rocks are known from Caledonian time, while the Variscan metamorphism in Europe was of the low-pressure type (ZWART 1967). Now, for a hypothetical high-pressure metamorphic rock of Caledonian age one would expect a strong metamorphic overprint of Variscan time due to the wide extent of this latter metamorphism in the Lepontine and adjacent areas (FREY et al. 1976, Fig. 2).

Geological evidence relevant to the possible existence of an early Alpine metamorphism does not exist along the Geotraverse, because higher tectonic units (Upper Pennine and Austroalpine nappes) are missing today. However, some combined stratigraphic and tectonic evidence can be brought up from the western side of the Lepontine area. The Barrhorn series, traditionally thought to be the autochthonous to parautochthonous cover of the Bernhard nappe, comprises a stratigraphic sequence of Upper Cretaceous and Lower(?) Tertiary (ELLENBERGER 1952). Thus it would seem unlikely that an early Alpine metamorphism was taking place in the more external lower Pennine zone, while sedimentation was still going on in the south and also in the north (Helvetic zone). We are aware of the fact that this argument should be used with caution because the Barrhorn series is located some 75 km to the west of the Geotraverse (and may even be allochthonous!).

At present there exists some debate concerning the precise dating of the Tertiary metamorphism in the Lepontine area by geochronological methods. According to JÄGER (1973) the peak of this metamorphism occurred 35-38 my ago. This conclusion is essentially based on Rb-Sr phengite ages from the western periphery of the Lepontine area, about 70 km west of the Geotraverse. These ages are interpreted to date the crystallization of the phengites which formed below the closing temperature for their Rb-Sr system of about 500 °C. The relevant isotopic ages in the high metamorphic, central part of the Lepontine area are 10-15 my younger, but their significance with respect to the metamorphic evolution is only partly understood. Only one single Rb-Sr phengite age value, from the Rotondo granite (JÄGER 1979), belongs to the 35-38 my age group.

KÖPPEL & GRÜNENFELDER (1975, 1978 and pers. comm. 1980) used concordant U-Pb monazite ages to date the Lepontine metamorphism. A regular age pattern was found in the Geotraverse section, with ages of 28-31 my along the "root zone" and with the youngest ages of 21-23 my occurring in the tectonically deepest Leventina unit further to the north (Fig. 3). According to JÄGER (1979, p. 8) monazite ages date a stage during the cooling process. On the other hand, KÖPPEL & GRÜNENFELDER interpret these ages as the time of monazite crystallization, indicating that high-temperature metamorphic conditions prevailed until 30 my in the "root zone" and until 21 my in the Leventina gneiss. A similar conclusion was reached by HÄNNY et al. (1975) for the Bodengo area in the eastern part of the Lepontine gneiss region. Based on small-scale whole rock Rb-Sr isochrons and U-Pb monazite ages these authors concluded that high-grade metamorphic conditions still existed at about 23 my ago. More investigations are needed for a better understanding of the significance of the U-Pb monazite ages and Rb-Sr small-scale whole rock ages.

The first attempt to date orogenic phases by isotope methods was undertaken by STEIGER (1964), who performed a combined petrofabric and K-Ar isotopic study on hornblendes of the Tremola series, southern Gotthard Massif. Randomly oriented hornblendes of the third generation yielded ages of 23-30 my and may represent cooling or formation ages related to the metamorphism of the Lepontine area. Three N-S oriented hornblendes gave an age of 46 my, which was interpreted as a minimum age for major nappe movements in this region. Since no other such age values have been found from the Central Alps, their significance remains unclear. Partially oriented hornblendes could not be related to any particular event; apparent ages range from 23 my up to 112 my. These high values may point to a pre-Alpine origin for these hornblendes which suffered differential argon loss during Alpine time.

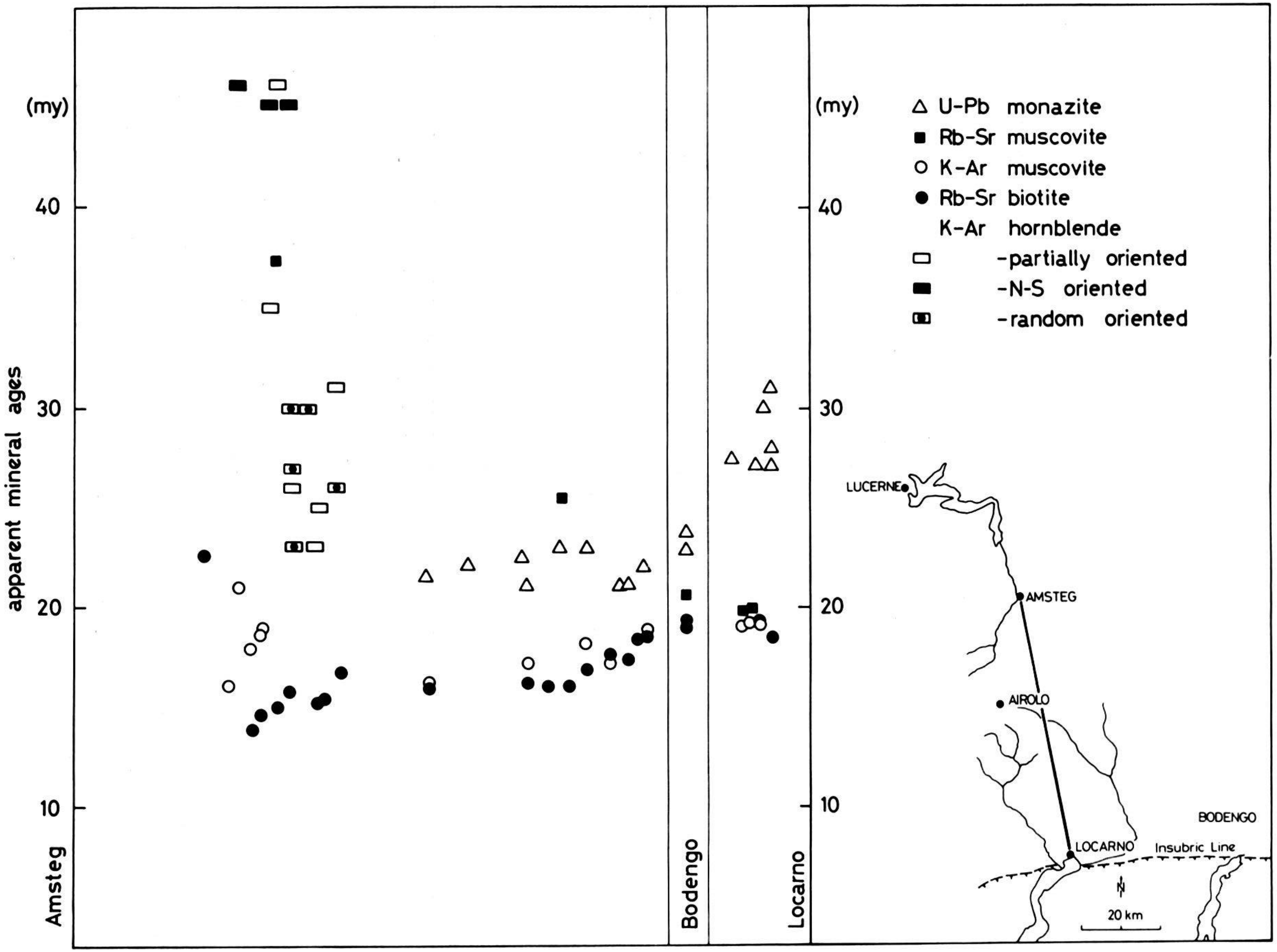


Fig. 3. Summary of apparent mineral ages in a profile between Amsteg and Locarno. Results from the Bodengo area are shown for comparison. Sources of data are as follows: HÄNNY et al. (1975), JÄGER (1969, 1979), JÄGER et al. (1967), KÖPPEL & GRÜNENFELDER (1975, 1978 and unpublished results), PURDY & JÄGER (1976), STEIGER (1964), STEIGER & BUCHER (1978), WAGNER et al. (1977).

The numerous Rb-Sr biotite ages determined from the Lepontine area (and the Gotthard Massif) systematically increase from 14 my in the north to 19 my in the south along our cross section (Fig. 3). This simple pattern cuts the zones of Alpine metamorphism as well as the tectonic boundaries and reflects the cooling history of the area (JÄGER et al. 1967): The biotite ages indicate the time when these rocks passed the blocking temperature of about 300 °C during cooling and the biotites became closed with respect to radiogenic Sr. The regional age pattern implies a differential cooling and uplift history along our profile, with faster cooling in the south. The general validity of the interpretation of Rb-Sr biotite ages as cooling ages is questionned by STEIGER & BUCHER (1978). They propose a test method and tentatively conclude that Rb-Sr ages for coarse-grained crossbiotite in the Tremola series (15 my) represent the age of formation. More work is needed to evaluate this proposition.

Geologic evidence summarized by TRÜMPY (1980, p. 92) as well as preliminary radiometric ages (HUNZIKER 1979) do not yet allow to decide whether the low-grade metamorphism in the northern part of the Geotraverse (Helvetic nappes, Aar Massif) was of the same age or definitely younger than the Lepontine metamorphism.

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## REFERENCES

ADAMS, H. G., COHEN, L. H., & ROSENFELD, J. G. (1975): *Solid inclusion piezothermometry: II. Geometric basis, calibration for the association quartz-garnet, and application to some pelitic schists.* - Amer. Mineralogist *60*, 584-598.

AMBÜHL, E. (1929): *Petrographie und Geologie des zentralen Gotthardmassivs südlich Andermatt.* - SMPM *9*, 265-441.

ARNOLD, A. (1970): *Die Gesteine der Region Nalps-Curnera im nordöstlichen Gotthardmassiv, ihre Metamorphose und ihre Kalksilikatfels-Einschlüsse.* - Beitr. geol. Karte Schweiz [N.F.] *138*.

AYRTON, S. N., & RAMSAY, J. G. (1974): *Tectonic and Metamorphic Events in the Alps.* - SMPM *54*, 609-639.

BERNOTAT, W. H., & BAMBAUER, H. U. (1980): *Die Mikroklin/Sanidin-Isograde in Aar- und Gotthardmassiv.* - Eclogae geol. Helv. *73/2*.

BREITSCHMID, A. (1980): *Diagenese und schwache Metamorphose in den sedimentären Abfolgen der Zentralschweizer Alpen (Vierwaldstätter See-Uri-Rotstock).* - Diss. Univ. Bern.

BÜHL, H. (1980): *Petrographie, Metamorphose und Strukturen in der Zone von Bellinzona im Gebiete des Corno di Gesero.* - Diplomarb. ETH Zürich.

DIETRICH, V., VUAGNAT, M., & BERTRAND, J. (1974): *Alpine Metamorphism of Mafic Rocks.* - SMPM *54*, 291-332.

DUNOYER DE SEGONZAC, G., & BERNOULLI, D. (1976): *Diagenèse et métamorphisme des argiles dans le Rhétien Sud-alpin et Austroalpin (Lombardie et Grisons).* - Bull. Soc. géol. France *18*, 1283-1293.

ELLENBERGER, F. (1952): *Sur l'extension des faciès briançonnais en Suisse, dans les Préalpes médianes et les Pennides.* - Eclogae geol. Helv. *45*, 285-286.

England, P.C., & Richardson, S.W. (1977): *The influence of erosion upon the mineral facies of rocks from different metamorphic environments.* - J. geol. Soc. (London) *134*, 201-213.
Ernst, W.G. (1973): *Interpretative Synthesis of Metamorphism in the Alps.* - Bull. geol. Soc. Amer. *84*, 2053-2078.
— (1978): *Petrochemical Study of Lherzolitic Rocks from the Western Alps.* - J. Petrol. *19*/3, 341-392.
Eugster, H.P., & Skippen, G.B. (1967): *Igneous and Metamorphic Reactions Involving Gas Equilibria.* In: Abelson, Ph. H. (Ed.): *Researches in Geochemistry* (Vol. 2, 492-520). - Wiley, New York.
Evans, B.W., & Trommsdorff, V. (1970): *Regional metamorphism of ultramafic rocks in the Central Alps: Parageneses in the system* $CaO$-$MgO$-$SiO_2$-$H_2O$. - SMPM *50*, 481-492.
— (1978): *Petrogenesis of garnet lherzolite, Cima di Gagnone, Lepontine Alps.* - Earth and planet. Sci. Lett. *40*, 333-348.
Evans, B.W., Trommsdorff, V., & Richter, W. (1979): *Petrology of an eclogite-metarodingite suite at Cima di Gagnone, Ticino, Switzerland.* - Amer. Mineralogist *64*, 15-31.
Fox, J.S. (1974): *Petrology of some low-variance meta-pelites from the Lukmanier Pass area, Switzerland.* - Ph. D. thesis, Cambridge Univ.
— (1975): *Three-dimensional isograds from the Lukmanier Pass, Switzerland, and their tectonic significance.* - Geol. Mag. *112*, 547-564.
Frank, E. (1979): *Metamorphose mesozoischer Gesteine im Querprofil Brig-Verampio: Mineralogisch-petrographische und isotopengeologische Untersuchungen.* - Diss. Univ. Bern.
Frey, M. (1974): *Alpine Metamorphism of Pelitic and Marly Rocks of the Central Alps.* - SMPM *54*, 489-506.
— (1978): *Progressive Low-Grade Metamorphism of a Black Shale Formation, Central Swiss Alps, with Special Reference to Pyrophyllite and Margarite Bearing Assemblages.* - J. Petrol. *19*, 95-135.
Frey, M., & Wieland, B. (1975): *Chloritoid in autochthon-parautochthonen Sedimenten des Aarmassivs.* - SMPM *55*, 407-418.
Frey, M., Hunziker, J.C., Frank, W., Bocquet, J., Dal Piaz, G.V., Jäger, E., & Niggli, E. (1974): *Alpine Metamorphism of the Alps. A Review.* - SMPM *54*, 247-290.
Frey, M., Jäger, E., & Niggli, E. (1976): *Gesteinsmetamorphose im Bereich der Geotraverse Basel-Chiasso.* - SMPM *56*, 649-659.
Frey, M., Teichmüller, M., Teichmüller, R., Mullis, J., Künzi, B., Breitschmid, A., Gruner, U. & Schwizer, B. (1980): *Very low-grade metamorphism in external parts of the Central Alps: Illite crystallinity, coal rank and fluid inclusion data.* - Eclogae geol. Helv. *73*/1, 173-203.
Fumasoli, M.W. (1974): *Geologie des Gebietes nördlich und südlich der Iorio-Tonale-Linie im Westen von Gravedona (Como, Italia).* - Diss. Univ. Zürich.
Grubenmann, U. (1904): *Die kristallinen Schiefer.* - Bornträger, Berlin.
Hänny, R., Grauert, B., & Soptrajanova, G. (1975): *Paleozoic Migmatites Affected by High-Grade Tertiary Metamorphism in the Central Alps (Valle Bodengo, Italy).* - Contr. Mineral. Petrol. *51*, 173-196.
Heinrich, C. (1978): *Metamorphose und Strukturen der Cima-Lunga Serie. I. Cima di Gagnone-Val Motta.* - Diplomarb. ETH Zürich.
Heitzmann, P. (1975): *Zur Metamorphose und Tektonik im südöstlichen Teil der Lepontinischen Alpen (Provincia di Como, Italia).* - SMPM *55*, 467-522.
Hiss, B. (1978): *Feldspäte als petrogenetische Indikatoren in granitoiden Gneisen des Lepontins.* - SMPM *58*, 243-288.
Hoefs, J., & Stalder, H.A. (1977): *Die C-Isotopenzusammensetzung von* $CO_2$*-haltigen Flüssigkeitseinschlüssen in Kluftquarzen der Zentralalpen.* - SMPM *57*, 329-347.
Hoernes, S., & Friedrichsen, H. (1980): *Oxygen and hydrogen-isotopic composition of Alpine- and pre-Alpine minerals of the Swiss Central Alps.* - Contr. Mineral. Petrol. *72*, 19-32.
Huber, M., Ramsay, J., & Simpson, C. (1980): *Deformation in the Maggia and Antigorio Decken, Lepontine Alps.* - Eclogae geol. Helv. *73*/2.
Hunziker, J.C. (1979): *Potassium Argon Dating.* In: Jäger, E., & Hunziker, J.C. (Ed.): *Lectures in Isotope Geology* (p. 52-76). - Springer, Berlin.
Irouschek, A. (1978): *Untersuchungen an Metapeliten der Campo Tencia-Masse unter besonderer Berücksichtigung des Na-Gehaltes von Muskovit.* - Diplomarb. Univ. Basel.
Jäger, E. (1969): *Geochronology of Phanerozoic Orogenic Belts.* - Guide Book, Field Trip, Switzerland.

— (1973): *Die alpine Orogenese im Lichte der radiometrischen Altersbestimmung.* - Eclogae geol. Helv. *66*/1, 11-21.

— (1979): *The Rb-Sr Method.* In: JÄGER, E., & HUNZIKER, J.C. (Ed.): *Lectures in Isotope Geology* (p. 13-26). Springer, Berlin.

JÄGER, E., NIGGLI, E., & WENK, E. (1967): *Rb-Sr-Altersbestimmungen an Glimmern der Zentralalpen.* - Beitr. geol. Karte Schweiz [N.F.] *134.*

JENNI, J.-P. (1973): *Die Vorkommen von Bleiglanz, Kupferkies und Zinkblende des Bristenstocks (Kt. Uri).* - Beitr. Geol. Schweiz, geotech. Ser. *53.*

KELLER, F. (1968): *Mineralparagenesen und Geologie der Campo Tencia-Pizzo Forno-Gebirgsgruppe.* - Beitr. geol. Karte Schweiz [N.F.] *135.*

KISCH, H.J. (1980): *Illite crystallinity and coal rank associated with lowest-grade metamorphism of the Taveyanne greywacke in the Helvetic zone of the Swiss Alps.* - Eclogae geol. Helv. *73*/3 (in press).

KLAPER, E. (1980): *Strukturen, Deformation und Metamorphose in der nördlichen Maggia-Zone.* - Diplomarb. ETH Zürich.

KLEIN, H.-H. (1976*a*): *Metamorphose von Peliten zwischen Rheinwaldhorn und Pizzo Paglia (Adula- und Simano-Decke).* - SMPM *56*, 457-479.

— (1976*b*): *Alumosilikatführende Knauern im Lepontin.* - SMPM *56*, 435-456.

KÖPPEL, V., & GRÜNENFELDER, M. (1975): *Concordant U-Pb ages of monazite and xenotime from the Central Alps and the timing of high temperature Alpine metamorphism, a preliminary report.* - SMPM *55*, 129-132.

— (1978): *The significance of monazite U-Pb ages: examples from the Lepontine area of the Swiss Alps.* In: ZARTMAN, R.E. (Ed.): *Fourth International Conference, Geochronology, Cosmochronology, Isotope Geology* (p. 226-227). - Geol. Surv. Open-File Rep.

LOIDA, A. (1979): *Die Kristallchemie von Granat und die Triklinität der Alkalifeldspäte als petrogenetische Indikatoren in Verbindung mit der Kristallisationsgeschichte granitischer Gesteine des Gotthardmassivs/Schweiz.* - Diss. Univ. Marburg.

MARTINI, J., & VUAGNAT, M. (1965): *Présence du facies à zéolites dans la formation des «grès» de Taveyanne (Alpes franco-suisses).* - SMPM *45*, 281-293.

MERCOLLI, I. (1979): *Le inclusioni fluide nei noduli di quarzo dei marni dolomitici della regione del Campolungo (Ticino).* - Diss. ETH Zürich.

MILNES, A.G. (1974): *Post-Nappe Folding in the Western Lepontine Alps.* - Eclogae geol. Helv. *67*, 333-348.

— (1975): *On Steep Isogradic Surfaces in the Simplon Area: A Discussion.* - Contr. Mineral. Petrol. *53*, 65-68.

— (1976): *Strukturelle Probleme im Bereich der Schweizer Geotraverse - das Lukmanier-Massiv.* - SMPM *56*, 615-618.

MILNES, A.G., & SCHMUTZ, H.-U. (1978): *Structure and history of the Suretta nappe (Pennine zone, Central Alps) - a field study.* - Eclogae geol. Helv. *71*, 19-33.

MÖCKEL, J.R. (1969): *Structural petrology of the garnet-peridotite of Alpe Arami (Ticino, Switzerland).* - Leidse geol. Meded. *42*, 61-130.

MULLIS, J. (1979): *The system methane-water as a geologic thermometer and barometer from the external part of the Central Alps.* - Bull. Minéral. *102*, 526-536.

NIGGLI, E. (1970): *Alpine Metamorphose und alpine Gebirgsbildung.* - Fortschr. Mineral. *47*, 16-26.

NIGGLI, E., & NIGGLI, C. (1965): *Karten der Verbreitung einiger Mineralien der alpidischen Metamorphose in den Schweizer Alpen (Stilpnomelan, Alkali-Amphibol, Chloritoid, Staurolith, Disthen, Sillimanit).* - Eclogae geol. Helv. *58*, 335-368.

PFEIFER, H.R. (1978): *Hydrothermal Alpine metamorphism in metaperidotite rocks of the Cima Lunga zone, Valle Verzasca, Switzerland.* - SMPM *58*, 400-405.

— (1979): *Fluid-Gesteins-Interaktion in metamorphen Ultramafititen der Zentralalpen.* - Diss. ETH Zürich.

POTY, B.P., STALDER, H.A., & WEISBROD, A.M. (1974): *Fluid Inclusions Studies in Quartz from Fissures of Western and Central Alps.* - SMPM *54*, 717-752.

PURDY, J.W., & JÄGER, E. (1976): *K-Ar ages on rock-forming minerals from the Central Alps.* - Mem. Ist. geol. Univ. Padova *30.*

ROSENFELD, J.L. (1969): *Stress effects around quartz inclusions in almandine and the piezothermometry of coexisting aluminium silicates.* - Amer. J. Sci. *267*, 317-351.

— (1978): *Snowball muscovite in the Central Swiss Alps: an internal recorder of tectonometamorphism.* - Abstr. geol. Soc. Amer. (with programs) *10/7*.

SCHAER, J.P., REIMER, G.M., & WAGNER, G.A. (1975): *Actual and ancient uplift rate in the Gotthard region, Swiss Alps: A comparison between precise levelling and fission-track apatite age.* - Tectonophysics *29*, 293-300.

SCHENKER, F. (1980): *Geologische und mineralogische Untersuchungen im Gebiet der grossen und kleinen Windgälle, Maderanertal, Kt. Uri.* - Liz.-Arb. Univ. Bern.

SCHLÄPFER, E. (1979): *Metamorphose und Strukturen der Cima Lunga Serie. IV. Val d'Efra-Val Gagnone.* - Diplomarb. ETH Zürich.

STALDER, P.J. (1979): *Organic and inorganic metamorphism in the Taveyannaz sandstone of the Swiss Alps and equivalent sandstones in France and Italy.* - J. sediment. Petrol. *49*, 463-481.

STÄUBLE, J. (1978): *Metamorphose und Strukturen der Cima Lunga Serie. II. Val Agro.* - Diplomarb. ETH Zürich.

STECK, A. (1976): *Albit-Oligoklas-Mineralgesellschaften der Peristeritlücke aus alpinmetamorphen Granitgneisen des Gotthardmassivs.* - SMPM *56*, 269-292.

STECK, A., & BURRI, G. (1971): *Chemismus und Paragenesen von Granaten aus Granitgneisen der Grünschiefer- und Amphibolitfazies der Zentralalpen.* - SMPM *51*, 534-538.

STEIGER, R.J. (1964): *Dating of orogenic phases in the Central Alps by K-Ar ages of hornblende.* - J. geophys. Res. *69*, 5407-5421.

STEIGER, R.J., & BUCHER, I. (1978): *Are Rb-Sr biotite ages in the Central Alps necessarily cooling ages?* - In: ZARTMAN, R.E. (Ed.): *Fourth International Conference, Geochronology, Cosmochronology, Isotope Geology* (p. 414-415). - Geol. Surv. Open File Rep.

THOMPSON, P.H. (1976): *Isograd Patterns and Pressure-Temperature Distributions During Regional Metamorphism.* - Contr. Mineral. Petrol. *57*, 277-295.

TROMMSDORFF, V. (1966): *Progressive Metamorphose kiesliger Karbonatgesteine in den Zentralalpen zwischen Bernina und Simplon.* - SMPM *46*, 431-460.

TROMMSDORFF, V., & EVANS, B.W. (1974): *Alpine Metamorphism of Peridotitic Rocks.* - SMPM *54*, 333-352.

TRÜMPY, R. (1980): *Geology of Switzerland. A Guide-Book. Part A: An Outline of the Geology of Switzerland.* - Wepf, Basel.

VOGLER, W.S., & VOLL, G. (1976): *Fabrics and Metamorphism from Tonalite, Granitic Augen Gneiss and Tonale Series at the S-Margin of the Swiss Alps, E of Bellinzona.* - SMPM *56*, 635-640.

VOLL, G. (1976): *Recrystallization of Quartz, Biotite and Feldspars from Erstfeld to the Leventina Nappe, Swiss Alps, and its Geological Significance.* - SMPM *56*, 641-647.

WAGNER, G.A., REIMER, G.M., & JÄGER, E. (1977): *Cooling ages derived by apatite fission-track, mica Rb-Sr and K-Ar dating: the uplift and cooling history of the Central Alps.* - Mem Ist. geol. Univ. Padova *30*.

WENK, E. (1968): *Cordierit in Val Verzasca.* - SMPM *48*, 455-457.

— (1970): *Zur Regionalmetamorphose und Ultrametamorphose im Lepontin.* - Fortschr. Mineral. *47*, 34-51.

— (1979): *Bevorzugte Zusammensetzung und Variabilität der Plagioklase von Gesteinsserien der Verzasca.* - N. Jb. Miner. [Mh.] *12*, 525-541.

WENK, E., & KELLER, F. (1969): *Isograde in Amphibolitserien der Zentralalpen.* - SMPM *49*, 157-198.

WENK, E., & WENK, H.-R. (1977): *An-Variation and Intergrowths of Plagioclases in Banded Metamorphic Rocks from Val Carecchio (Central Alps).* - SMPM *57*, 41-57.

WERNER, D., KÖPPEL, V., HÄNNY, R., & RYBACH, L. (1976): *Cooling Models for the Lepontine Area (Central Swiss Alps).* - SMPM *56*, 661-667.

WINKLER, H.G.F. (1979): *Petrogenesis of Metamorphic Rocks.* - Springer, New York.

ZINGG, A.J. (1979): *Metamorphose und Strukturen der Cima Lunga Serie. III. Cima d'Efra-Cima di Nedro.* - Diplomarb. ETH Zürich.

ZWART, H.J. (1967): *The duality of orogenic belts.* - Geol. en Mijnb. *46*, 283-309.

SMPM = Schweiz. mineral. petrogr. Mitt.