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Movements and Metamorphism North of the Insubric Line between Val Loana and Val d'Ossola (Italy)

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With 8 Figures

Westalpen
Tektonik
Metamorphose
Gefügekunde
Insubrische Linie
Temperaturflächen
Rekristallisationskorngrößen

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Abstract

In the study area the alpine metamorphism reached medium amphibolite facies heading in the NW direction whereas near the Insubric Line the upper boundary of greenschist facies was touched barely. The oligoclase boundary, the beginning of feldspar recrystallisation, the chloritoid-staurolite transition and the lines of equal size of recrystallized feldspar grains reflect the distribution of maximum temperature during alpine metamorphism. The planes of equal temperature show a moderate plunge towards the NW.

In the Monte Rosa Nappe and the northern part of the Gneiss Zone, NW of the Insubric Line, deformation was mainly outlasted by the annealing. Towards the Insubric Line, deformation still occurred during decreasing temperatures and was accumulated in a mylonite zone along the Insubric Line, still active under lower greenschist facies conditions. Despite great local variation the stretching direction as well as the asymmetry of third folds indicate a general vertical movement in the area north to the Insubric Line and, at least during the last stage of deformation, an upward thrusting of the Central Alps relative to the Southern Alps.

Zusammenfassung

Im untersuchten Gebiet lief die alpine Metamorphose im NW unter Bedingungen der mittleren Amphibolitfazies ab, während im SE nahe der Insubrischen Linie die Obergrenze der Grünschieferfazies gerade noch erreicht wurde. Die Oligoklas-Grenze, der Beginn der Feldspat-Rekristallisation, der Übergang von Chloritoid zu Staurolith und die Linien gleicher Rekristallisationskorngrößen von Feldspäten spiegeln die Verteilung der Maximaltemperaturen während der alpinen Metamorphose wieder. Die Flächen gleicher Maximaltemperatur fallen mittelsteil nach NW ein.

Die Deformation wurde in der Monte Rosa-Decke und im nördlichen Teil der Gneiszone, nordwestlich der Insubrischen Linie, generell von der Temperung überdauert. Nahe der Insubrischen Linie war die Deformation auch noch bei sinkenden Temperaturen aktiv und konzentrierte sich bei Bedingungen der unteren Grünschieferfazies in einer Mylonitzone entlang der Insubrischen Linie. Trotz großer örtlicher Variationen läßt sich aus der Streckungsrichtung und auch aus der Asymmetrie dritter Falten eine generelle Vertikalbewegung im Gebiet nördlich der Insubrischen Linie ableiten und – zumindest während der letzten Deformationsphase – eine Hochbewegung der Zentralalpen gegenüber den Südalpen.

1. Introduction

Investigations on the Gneiss Zone (Alpine "Root Zone") between Val d'Ossola and Finero (REINHARDT, 1966; KRUHL & VOLL, 1976; KRUHL, 1979; SCHMID et al., 1987) lead to concepts on the metamorphic and structural development of this zone. In the present study we will add some informations especially on alpine structures and heating in the area between Val Loana and Val d'Ossola (fig. 1).

Most of field and laboratory work for this study has been done between 1980 and 1983. After a delay of

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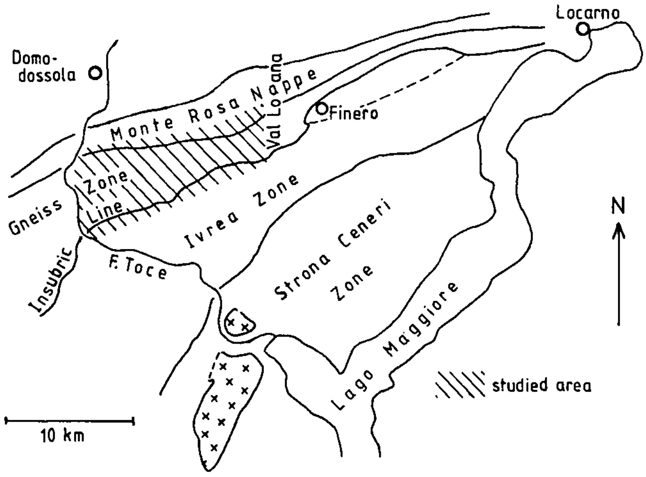

Fig. 1.
Location of the study area within the Western Alps.

nearly two years by the Schweiz. mineral. petrogr. Mitt. recent publications have been considered for the present revised version. Since geological strain rates are rather low we think that our contribution is still timely.

In general, the rock sequence in this part of the Gneiss Zone north of the Insubric Line is the same as further to the NE and is described in detail elsewhere (REINHARDT, 1966; KRUHL & VOLL, 1976). To the north the Gneiss Zone borders the augengneisses of the Monte Rosa Nappe – with numerous intercalated aplites and pegmatites. The southern boundary of the Gneis Zone is formed by the Insubric Line and the high metamorphic rocks of the Ivrea Zone: quartz-plagioclase-biotite gneisses, kinzigitic gneisses with sillimanite, amphibolites with relics of ortho- and clinopyroxene, pegmatites and lense-shaped intercalations of marbles which contain, besides calcite and quartz, plagioclase (An 50), diopside and scapolite. Further descriptions of the situation south of the Insubric Line are already given by SCHMID (1967).

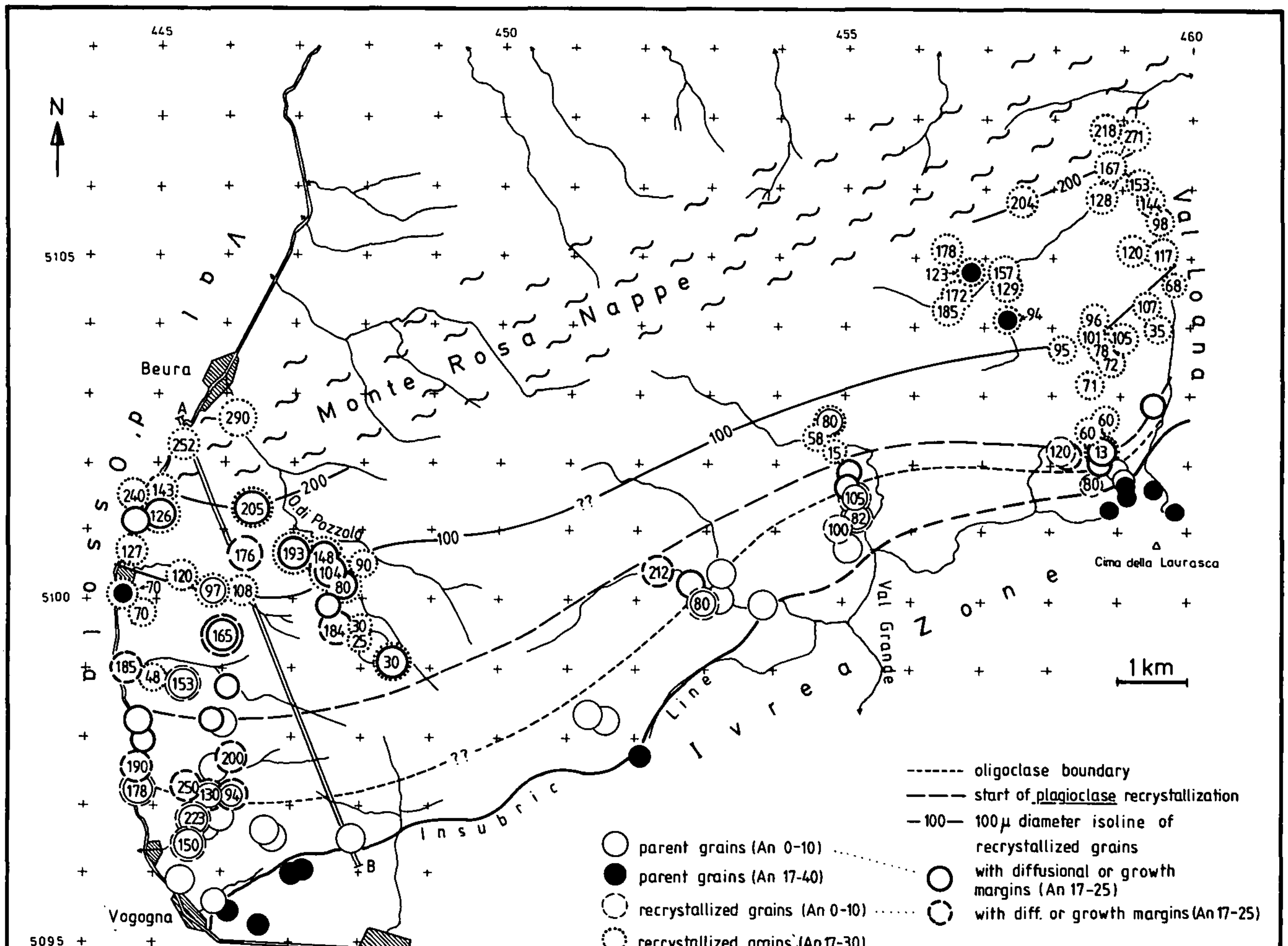

Fig. 2.
An contents and recrystallization features of Alpine and pre-Alpine plagioclase within the Gneiss Zone northwest of the Insubric Line between Val Loana and Val d'Ossola. Presented are
1) The Alpine oligoclase boundary (change from albite to oligoclase at about 500°C, according to VOLL, 1968);
2) start of the Alpine recrystallyzation of plagioclase at about 510–520°C;
3) the average diameters of Alpine recrystallized plagioclase grains [µ], evaluated through 50–100 thin section measurements for each sample;
4) the average diameters of preserved pre- or early Alpine plagioclase (albite) grains;
5) the occurrence of Alpine oligoclase diffusional or growth margins at albites;
6) the An content of pre-Alpine plagioclase south of the Insubric Line.
Furthermore the cross section A–B, used for fig. 4, is indicated. The Insubric Line is pictured after SCHMID (1967), KRUHL (1984) and the present study.

The variety of different rock types we encounter SW of Val Loana – as different types of gneisses, amphibolites, serpentinite-hornfelses, andesitic dikes, aplites and pegmatites – is reduced towards the SW. At Val d'Ossola we only find feldspar-mica gneisses, amphibolites, pegmatites, aplites and seldom carbonate-silicate rocks. In the total area the Insubric Line is followed by a 100 m (near Val Loana) to more than 1 km (near Val d'Ossola) wide mylonitic zone containing rocks both of the Gneiss Zone and of the Ivrea Zone.

2. Pre-alpine metamorphism

In contrast to the Ivrea rocks, north of the Insubric Line all rocks have been overprinted by alpine deformation and metamorphism. Nevertheless, we find indications of a former metamorphism which we interpret as a pre-alpine event. The indications are scarce near Val Loana and more frequent near Val d'Ossola, where the alpine deformation becomes considerably weak, and within that area north of the Insubric Line where the alpine temperature did not rise to more than 500°C, about the starting point of feldspar recrystallization (Voll, 1968, 1976):

At the southwest slope of Val Loana, in schistose gneisses, containing garnet and kyanite or andalusite, relics of sillimanite fibrolites occur as inclusions in quartz. Further to the south, directly north of the Insubric Line, there are relics of petrofabrics known from the gneisses and kinzigitic gneisses of the Ivrea Zone:

1) Garnets, partly altered to plagioclase or chlorite, with that pattern of netlike cracks typical for the Ivrea garnets and quite absent in the ±idiomorphic garnet crystals grown during alpine times;
2) coarse intergrowth of plagioclase and quartz (embayed structures) obviously not the result of the alpine upper greenschist facies metamorphism directly north of the Insubric Line (see further below);
3) Ti-rich biotite in gneisses;
4) within amphibolites green hornblende with a brown core and embayed structures between plagioclase and this brown core occurs. Moreover, relics of clinopyroxene are found within these rocks (fig. 5).

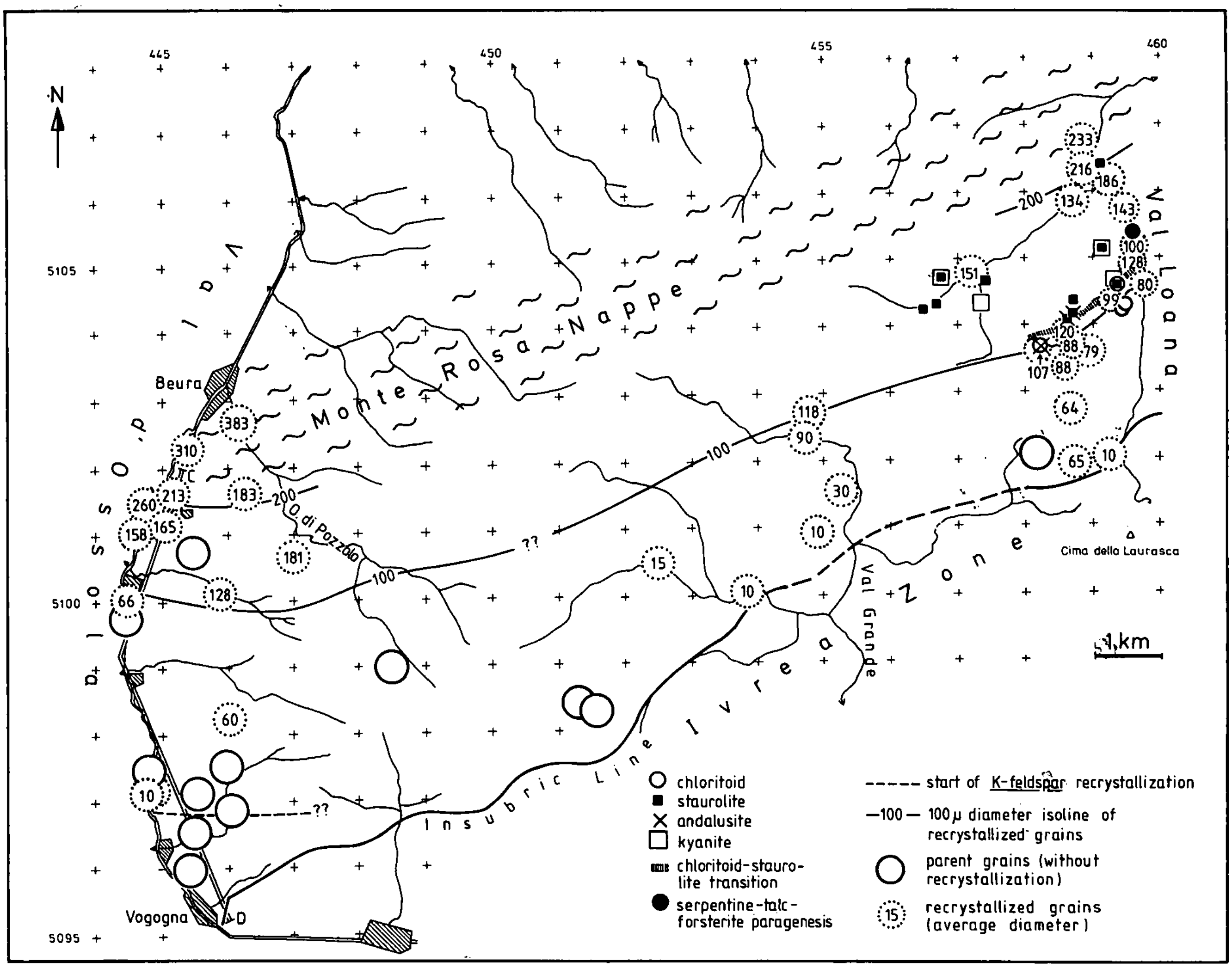

Fig. 3.
Alpine recrystallization features of K-feldspar within the Gneiss Zone northwest of the Insubric Line between Val Loana and Val d'Ossola. Presented are
1) the start of the recrystallization of K-feldspar, at about 480–490°;
2) the average diameters of recrystallized K-feldspar grains [μm], evaluated through 50–100 thin section measurements for each sample;
3) the occurrence of chloritoid, staurolite, andalusite and kyanite and the chloritoid–staurolite transition;
4) the occurrence of serpentine-talc-fosterite paragenesis at Val Loana (after Kruhl & Voll, 1976).
Furthermore the cross-section C–D, used for fig. 8, is indicated.

Towards Val d'Ossola where alpine deformation was rather weak relics of large albite grains surrounded by (possibly) recrystallized albite grains scarcely occur. Since they are found within rocks of rather high Ca-content, located near the plagioclase recrystallization isograde (see further below), and therefore not suitable for the formation of recrystallized albites of such a size, and since small exsoluted clinozoisite inclusions in the albite relics point to a former rather high An-content we interpret these grains as a result of a pre-alpine metamorphism. Of course, many of the albite relics abundant within the less deformed parts of the gneiss Zone might have grown early during increasing alpine metamorphism.

3. Alpine Metamorphism

The maximum alpine metamorphism within the Gneiss Zone between the Insubric Line and the southern margin of the Monte Rosa Nappe and between Val Loana and Val d'Ossola varies from upper greenschist facies to medium amphibolite facies (with increasing temperature from S to N). In general, this broad picture fits the division of mineral facies given by REINHARDT (1966) for the same region. However, there are differences in detail (see further below). During a late phase of deformation, mainly in the S, the temperature is down again in low greenschist facies (see also KRUHL, 1979, SCHMID et al., 1987).

The maximum alpine temperatures in the Gneiss Zone are indicated by deformation textures and mineral reactions as follows (figs. 2 and 3):

From S to N – with increasing maximum temperatures – first, K-feldspar recrystallization starts; second, albite crystals marginally change to oligoclase (oligoclase boundary); third, plagioclase recrystallization starts; fourth, chloritoid disappears and staurolite is formed. In figs. 2 and 3 these four transitions are presented for the region between Val Loana and Val d'Ossola. We may expect a temperature of about 530–540°C for the disappearence of chloritoid and the appearence of staurolite in the central Gneiss Zone (after RAO & JOHANNES, 1979), at the same temperature a pressure of about 5 Kb (after RICHARDSON et al., 1969) for the transition andalusite-kyanite (occuring at the same locality, see fig. 3), and a temperature of about 500°C for the oligoclase boundary (after VOLL, 1968). The temperature of about 580°C, presumed for the serpentine-forsterite-talk paragenesis within a lense of serpentine-hornfels in the Val Loana (KRUHL & VOLL, 1976), fits into the general temperature field as shown by the chloritoid-staurolite transition and the oligoclase boundary further to the S.

With the exception of the Mylonite Zone near the Insubric Line the maximum temperature was reached during the first alpine deformation. Quartz, feldspar, mus-

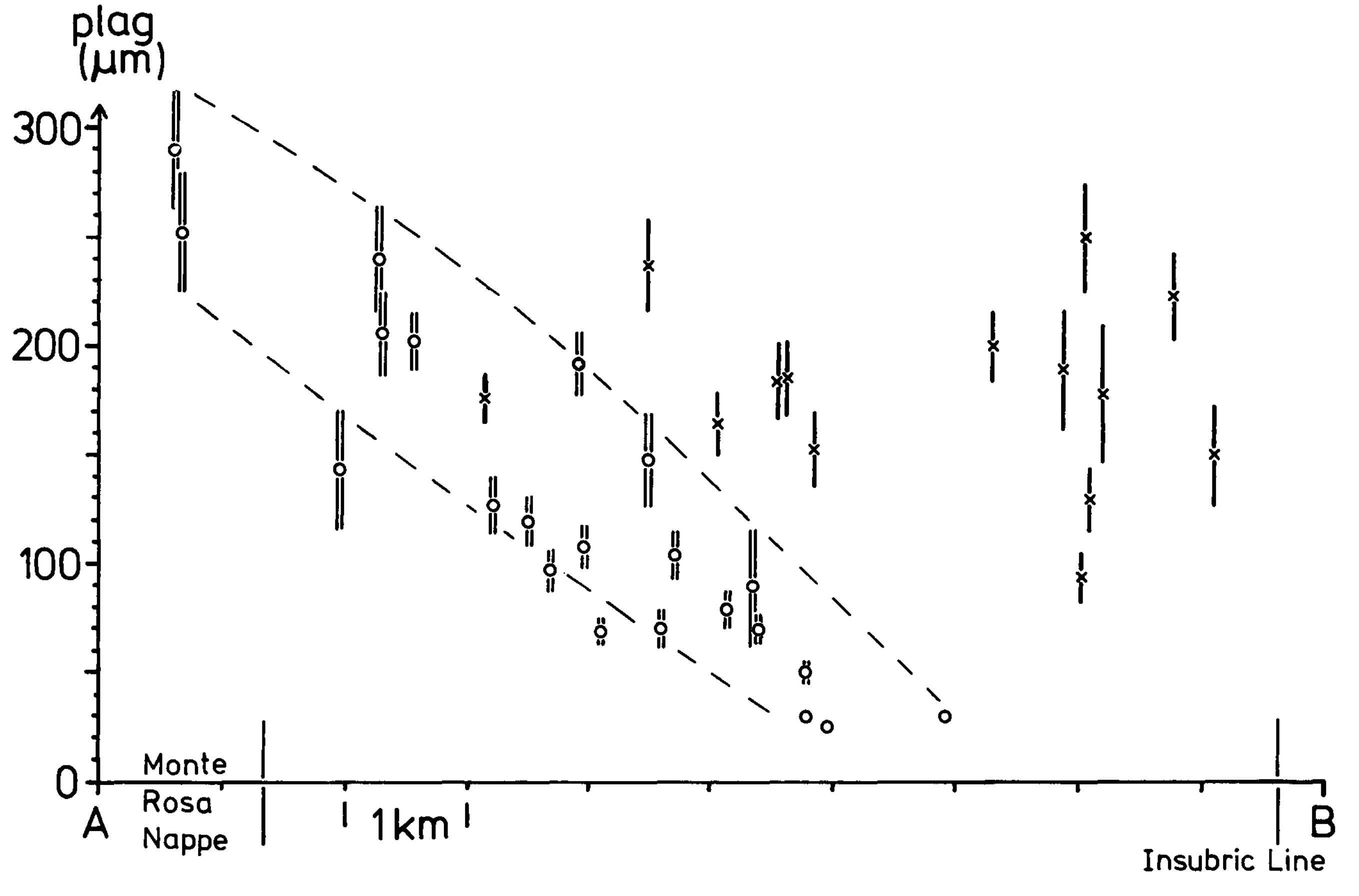

Fig. 4.
Alpine recrystallized (○) and pre- or early-Alpine (×) plagioclase grains from gneisses and augengneisses at Val d'Ossola. Presented are the average diameters, calculated through 50–100 thin section measurements for each sample, together with the confidence intervals for 95 % probability. The increase of diameters of the recrystallized plagioclase grains from N to S is unequivocal.
All the plagioclase measurements near Val d'Ossola, presented in fig. 2, have been used for this figure. The different positions of the samples in fig. 2 have been projected along the s_1 cleavage planes upon the cross-section A–B which is the x-co-ordinate in this diagram.

covite and biotite recrystallization as well as grain growth occurrred as a result of annealing. All minerals show signs of recovery. In quartz subgrain patterns are developed, without wavy extinction, and especially feldspars show polygonal grain shapes with straight or slightly curved boundaries and with equilibrium angles at triple points.

In general, the grainsize of recrystallized quartz, plagioclase, K-feldspar, biotite and muscovite increases from S to N. As an example the increase of plagioclase grainsize at Val d'Ossola is shown in fig. 4. The average diameters of albites, probably grown during increasing alpine metamorphism, and of recrystallized alpine plagioclases are plotted against the distance from the Insubric Line. The locations of the different samples, shown in fig. 2, are projected along the cleavage planes upon the cross-section A–B. The unequivocal increase of the size of alpine recrystallized grains is demonstrated by the lack of overlap of the confidence intervals (for 95 % probability) in the central part of the Gneiss Zone and the northern part respectively.

For the total Gneiss Zone the situation is shown in figs. 2 and 3. Lines of equal diameters of recrystallized plagioclase and K-feldspar grains are presented, together with the beginning of plagioclase and K-feldspar recrystallization, the oligoclase boundary and the chloritoid-staurolite transition. These lines are constructed on the basis of average values of graindiameters measured as follows.

1) Each number within the circles in figs. 2 and 3 represents the average grain diameter of 50–100 recrystallized grains measured in thin sections perpendicular to the alpine stretching direction.
2) Most of the samples come from augengneisses and from feldspar-mica gneisses.
3) To reduce the influence of a variable strength of deformation and the influence of neighbouring minerals, only certain grains have been measured, namely those placed in or at host grains or in lenses of former host grains, which do not contain other grainsize reducing minerals like micas or clinozoiste.

If we now assume no essential influence of neighbouring minerals and a nearly equal strain in all

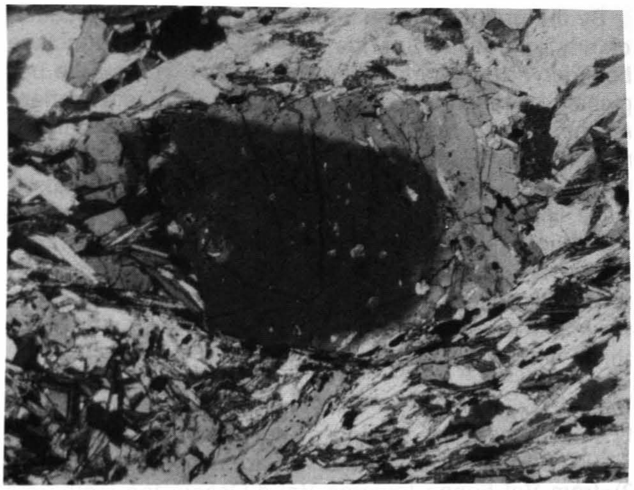

Fig. 6.
Pre- or early-Alpine albite with alpine growth margins of oligoclase. Gneiss from the northern part of the Gneiss Zone. Sample AL12 (R 446.30/H 5101.15). Nicols ×. The long side of the thin section photograph is about 3.4 mm.

the samples, we may interpret the final diameter of recrystallized grains mainly as a result of the thermal energy input during the time when the temperature is above 500°C, about the recrystallization temperature of feldspars. And consequently the lines of equal average diameters of recrystallized grains should represent lines of equal input of thermal energy. This idea has been introduced by Voll (1980) who showed that the mountains of the Aar- and Gotthard massiv can be zoned by subhorizontal planes of equal size of recrystallized quartz grains.

If we further assume that within the study area, i. e. within an area of only some km width, the time to heat up rocks to the same maximum temperature and cool down again is always the same at different localities, then those rocks heated up to the same temperature should show the same diameters of recrystallized feldspar grains. Through this we come to the idea that the lines of equal diameters of recrystallized grains roughly represent isotherms.

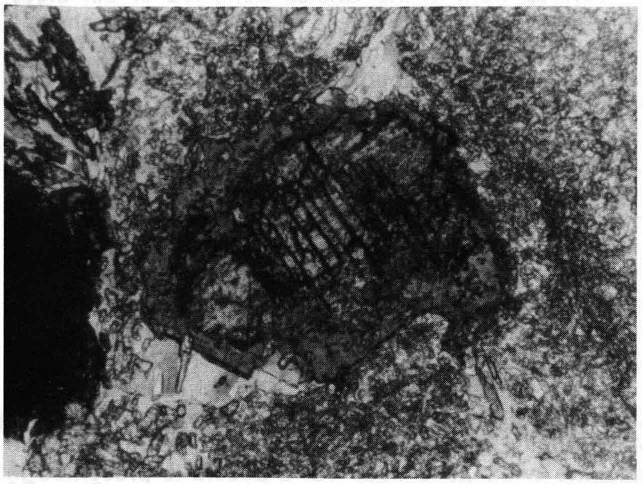

Fig. 5.
Relic of pre-Alpine clinopyroxene (with strong cleavage), surrounded by light green Alpine hornblende.
Amphibolite, ca. 0.5 km north of the Insubric Line. Sample 1981 from the Val Grande (R 455.04/H 5100/83). Nicols ‖. The long side of the thin section photograph is about 0.66 mm.

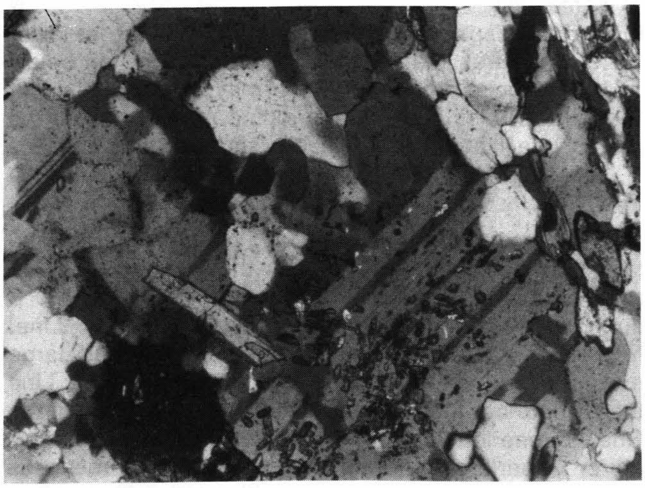

Fig. 7.
Relic of probably pre-Alpine plagioclase (now albite, twinned, with many inclusions of small clinozoisite crystals), surrounded by probably pre-Alpine recrystallized albite grains without clinozoisite inclusions.
Sample AL65 (R 445.71/H 5097.21). The long side of the thin section photograph is about 0.85 mm. Nicols ×.

By the grainsize measurements there is no indication of any intersection of the isolines and the oligoclase boundary, the chloritoid-staurolite transition and the beginning of plagioclase and K-feldspar recrystallization. All these lines result from one and the same regional metamorphism with ±uniform temperature distribution in this small area. That follows the assumption that all these lines are about parallel to one other.

On the basis of the measurements and the assumption of a rough parallelism, the isotherms mentioned above are plotted into the figs. 2 and 3. They reflect the maximum-temperature distribution of alpine metamorphism within the Gneiss Zone.

In figs. 2 and 3 it is shown that

1) the temperature zoning of the area north of Finero (KRUHL, 1979) continues towards the Val d'Ossola;
2) from Val Loana towards Val d'Ossola the isotherms deviate slightly from the Insubric Line towards the N;
3) the change from albite to oligoclase (oligoclase boundary) starts about 200 m (at Val Loana) to nearly 2 km (at Val d'Ossola) north of the Insubric Line, i. e. much more to the S than reported by REINHARDT (1966, fig. 36). About 10–30 µm wide diffusional or growth margins of oligoclase are formed around albite crystals. They increase rather discontinuously towards the N and at last consume all the host grains. At those localities with deformation too weak for a complete recrystallization of plagioclase, cores of albite surrounded by oligoclase margins are preserved, even in the most northerly parts of the Gneiss Zone (fig. 6). If plagioclase recrystallizes the new grains are always oligoclase;
4) the oligoclase boundary and the beginning of plagioclase recrystallization do not coincide;
5) both isotherms of beginning plagioclase recrystallization and of 100 µ diameter of recrystallized grains show nearly the same distance from each other at Val Loana and at Val d'Ossola, but at Val d'Ossola they remove from the oligoclase boundary. This could be the result of a reduced strength of deformation near Val d'Ossola. The high amount of pre- or early alpine plagioclase grains which survived the alpine deformation near Val d'Ossola points to the same fact;
6) the K-feldspar clearly starts to recrystallize at lower temperatures than the plagioclase, and even below the oligoclase boundary. We may infer: in this part of the Gneiss Zone during alpine metamorphism the recrystallization of K-feldspar starts at temperatures slightly below 500°C and the recrystallization of plagioclase begins slightly above 500°C.

If we consider that the beginning of K-feldspar recrystallization coincides roughly with the Insubric Line, we may expect a maximum temperature of about 480°C during alpine metamorphism at the Insubric Line. Nevertheless, possibly by strong shearing and large movements in the mylonites directly at the Insubric Line there could be a larger temperature-gradient than in the Gneiss Zone leading to a much lower maximum temperature. Quartz-chlorite-albite-clinozoisite parageneses and strong quartz deformation without or with just beginning recrystallization indicate mylonitization still active under conditions of low greenschist facies (see also SCHMID et al., 1987).

The isotherms, plotted in figs. 2 and 3, do not only provide information about the horizontal temperature distribution but also about the vertical one. If we understand these isotherms as intersections of planes of equal temperature and the surface of the earth, then we get temperature planes moderately plunging towards the NW, with a somewhat lower angle than the main cleavage planes and the compositional layering in the Gneiss Zone. The height difference of about 700 m at Val Loana and of about 1000 m at Val d'Ossola in combination with the values and the densitiy of the measurements should allow such a conclusion. This is in accordance with the steeply NW plunging temperature planes in the Gneiss Zone NE of Val Loana (KRUHL, 1979).

4. Pre-alpine Deformation

Presumably most of the rocks within the Gneiss Zone north of the Insubric Line have been part of a pre-alpine deformed and metamorphosed continental crust. We should expect within these rocks well developed planar textures as remnants of that pre-alpine deformation and metamorphism, especially quartz veins in gneissic and schistose rocks. From a limited region of the central Gneiss Zone REINHARDT (1966, 611–619) presents indications for relics of pre-alpine deformation textures as steep schistosity planes and fold axes. We think that in addition to these features and to the compositional layering in the cm to 100 m range most of the quartz veins in the zone originated from pe-alpine metamorphic and deformational events. We cannot give any statement on the pre-alpine stretching direction. Apparently it is either totally overprinted by alpine deformation or not discernable from alpine stretching directions. In general, the amount of relics of pre-alpine textures in the Gneiss Zone is rather uncertain.

5. Alpine Deformation and its Relationship to Metamorphism

Previous work in the Gneiss Zone NE of our study area (KRUHL, 1979; KRUHL & VOLL, 1976) has shown:

During alpine times the Gneiss Zone north of the Insubric Line and the southern margin of the Monte Rosa Nappe were mainly affected by four events of rotational deformation. Deformation occurred mainly during increasing temperatures and has been outlasted by the metamorphism. Nevertheless, during a late stage of metamorphism and decreasing temperatures along the Insubric Line shearing led to strong mylonitization. Directly SW of Val Loana the type of folds, cleavages and stretching directions and the relationship to metamorphism corresponds to the ones further to the NE, described in detail by KRUHL & VOLL (1976). For that reason we focus on the area near Val d'Ossola where the effect of alpine deformation is somewhat different. A schematic cross-section from the Monte Rosa Nappe into the Ivrea Zone near Val d'Ossola is presented in fig. 8.

First alpine deformation

Within the gneisses and augengneisses of the Monte Rosa Nappe one penetrative cleavage is developed. Large feldspar phenocrysts as well as small recrystal-

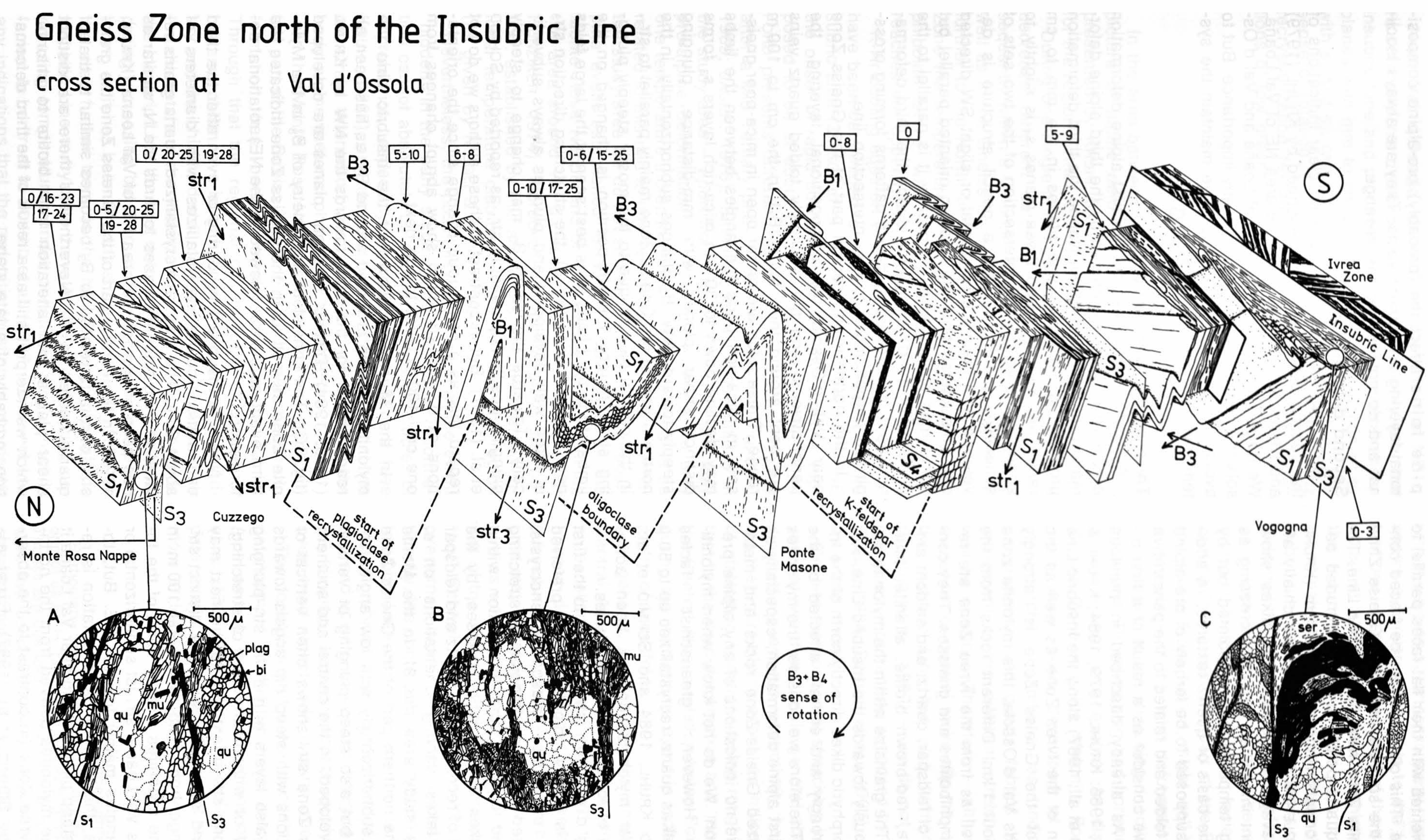

Fig. 8.
Schematic block diagram of the gneiss Zone at Val d'Ossola (cross-section C–D in fig. 3). Presented are the tectonic features of the distinct Alpine deformations, the start of the plagioclase and K-feldspar recrystallization, the oligoclase boundary, some An contents of plagioclase from gneisses, and thin section drawings from different parts of the Gneiss Zone and the southern margin of the Monte Rosa Nappe respectively (A–C), which show the different textures related to the temperature and the mylonitization.
A) Gneiss from the southern margin of the Monte Rosa Nappe, with s_1 and recrystallized quartz, plagioclase, biotite and muscovite. Quartz shows highly sutured boundaries and hardly ever polygonization; plagioclase has developed with mostly polygonal grain shapes. Sample 2317 (R 444.50/H 5100.76).
B) Gneiss with a quartz vein, folded by B_3. Main constituents are quartz, muscovite, biotite and ore. Quartz is recrystallized post B_3. Sample 2314 (R 444.41/H 5098.52).
C) Mylonite near the Insubric Line with quartz, muscovite, sericite, ore and some plagioclase. The mylonitic s_1 is folded between distinct s_3 shear planes. Again quartz is recrystallized during and after B_3. Sample 2294 (R 445.76/H 5095.39).

lized grains are oriented with their flat faces parallel to the cleavage plane. This cleavage can be traced continuously through the southerly adjacent Gneiss Zone and into the Mylonite Zone near the Insubric Line. Towards Val Loana quartz porphyric dikes, intruded before the alpine deformation and metamorphism (KRUHL & VOLL, 1976; VOGLER & VOLL, 1976), are chiefly affected by this cleavage; in general, the dikes show overprint of different intensities through increasing as well as decreasing temperatures, as pointed out by KRUHL (1986) on the basis of quartz textures. In addition, quartz veins, supposed to be largely of pre-alpine age, are isoclinally folded and related to the penetrative cleavage. All this we consider as a result of a first alpine deformation. As already described in previous studies (REINHARDT, 1966; KRUHL, 1979, 1984; KRUHL & VOLL, 1976; SCHMID et al., 1987) along the Insubric Line the northern margin of the Ivrea Zone as well as the southern margin of the Gneiss Zone ist strongly mylonitized. Towards Val d'Ossola, this mylonite zone grows wider to about 1 km. Different rocks from the Gneiss Zone as well as from the Ivrea Zone are reworked: marbles, amphibolites and gneisses. They contain porphyroblasts of feldspar, quartz, and seldom amphibolite, muscovite, red-brown biotite, allanite, tourmaline and zircon. The grainsize within the mylonite decreases discontinuously towards the Insubric Line. Additionally, quartz porphyric dikes directly north of the Insubric Line are strongly and entirely affected by the mylonitic foliation. Therefore we consider the mylonites as the result of a first alpine deformation, especially as within the mylonitized Gneiss-Zone rocks and metasediments there are no indications of any alpine premylonitic deformation. We do not know when mylonitization started. However, greenschist facies parageneses as well as quartz, recrystallized up to 50 μ diameter (see also KRUHL, 1984 and SCHMID et al., 1987), indicate that mylonitization has been active down to conditions of lower greenschist facies.

The stretching direction (str_1) related to the first alpine deformation is chiefly indicated by the preferred shape orientation of micas, feldspar phenocrysts, feldspar recrystallized grains, amphiboles, by stretching haloes around rigid crystals, and in addition within quartz-porphyric dikes and granitic gneisses, by the long axes of lenses of recrystallized quartz and feldspar respectively. str_1 takes varying orientations on s_1 planes through the study area (fig. 8): In the Monte Rosa Nappe and the northern part of the Gneiss Zone str_1 often plunges subhorizontally with low angles towards NE or SW, but also steep plunging or vertical orientations are developed. In the central and southern part of the Gneiss Zone str_1 shows often vertical or subvertical orientations with steep dip angels towards NE. But there are also layers with a flat str_1-plunging towards NE or SW or without any sign of stretching. The change from one str_1 orientation to the next may be rather abrupt and sequences with one distinct str_1 orientation may range from 1 cm to several 100 m in thickness. Within the mylonites directly north of the Insubric Line, towards Val Loana, str_1 ist subhorizontal or plunges with low angles mainly towards NE. But, towards Val d'Ossola, this preferential orientation is replaced by a rather steep plunging and near Val Loana it is not limited to the mylonites derived from the northern margin of the Ivrea Zone (in contrast to the observations presented by SCHMID et al., 1987). First alpine folds affect the (probably) pre-alpine compositonal layering and quartz veins. They are always isoclinal and do not exceed the m-range.

Second deformation

Near Val d'Ossola there are no clear indications of the second deformation, as described by KRUHL (1979) and KRUHL & VOLL (1976) for the area NE of Val Loana. We do not think that between Val Loana and Val d'Ossola the second deformation has any importance. But to avoid confusion of nomenclature we maintain the system given by KRUHL (1979).

Third alpine deformation

All textures produced by the first alpine deformation are more or less overprinted by the third alpine deformation. In the Monte Rosa Nappe the third deformation produces distinct cleavage planes in the mm to cm range (fig. 8A). Between these planes s_1 is slightly to strongly rotated. By the intersection of the two sets of schistosity planes in part a pencil structure is developed with mainly a horizontal or slight SW directed dip. This intersection line is often oriented parallel but sometimes oblique to str_1. Possibly it is parallel to the direction of quartz elongation during the third deformation as it is indicated by c-axis patterns forming crossgirdles perpendicular to the intersection line.

In the northern and central part of the Gneiss Zone near Val d'Ossola the compositional layering, the penetrative s_1 and the isoclinally folded quartz veins are bent around third folds (B_3) in the cm to 100 m range. These folds are rather open in mica-poor gneisses, in mica-rich parts the angles between the limbs may decline down to 30°. In mica-rich layers s_3 forms distinct shear planes with mm-distance, plunging steeply towards NW. B_3 plunges subhorizontally, in the northern part of the Gneiss Zone mainly parallel to str_1, in the central part oblique to the mostly steeply plunging str_1. Thereby the str_1-position is changed on the limbs of the third folds as is best seen at the large folds near Ponte Masone (fig. 8). the stretching direction str_3 is often well developed and plunges always subvertically. Towards the south B_3 may change to steeply plunging positions parallel to str_1 as reported by SCHMID et al. (1987). But in contrast to these authors we do not regard this as a continuous change since the orientations of B_3 and str_1 often show abrupt changes from one cm–100 m layer to the next.

In the Mylonite Zone at the Insubric Line the mylonitic foliation is folded around B_3, as has been already shown for the area towards the NW by KRUHL (1979, 1984). Distinct s_3 shear planes are developed (fig. 8C). The consistent asymmetry of B_3 in the Mylonite Zone as well as in the Gneiss Zone indicates the third event as dextral (viewed to the NE) rotational deformation.

Near the Insubric Line during or even after the third deformation quartz recrystallizes with diameters of about 30 μ. The size of recrystallized quartz grains related to third folds increases towards the N, similar as has been shown for the area NE of Val Loana (KRUHL, 1979). In the central part of the Gneiss Zone the grainsize of quartz related to B_3 becomes similar to that of quartz related to B_1. Nevertheless there are distinct shear planes with alteration from biotite to chlorite, which we interpret still as a result of the third deformation, probably of a late stage.

Near Val d'Ossola as well as towards the NE a fourth alpine deformation occurs mainly near the Insubric Line and produces distinct subhorizontal shear planes with mm to cm distance. The intersection of s_4 with s_1 and s_3, respectively, is subhorizontal. Again the sense of rotation is dextral (viewed to the NE). Quartz recrystallization textures indicate metamorphic conditions of low greenschist facies.

6. Discussion

In the area between Val Loana and Val d'Ossola the picture of alpine deformation and metamorphism, as presented by KRUHL & VOLL (1976) and KRUHL (1979) for the region further to the NE, is roughly corroborated:

During one single phase of temperature increase and decrease different deformational events occur subsequently within a Mylonite Zone at the Insubric Line as well as in the Gneiss Zone and the Monte Rosa Nappe further to the North. In the northern part of the Gneiss Zone the temperature maximum is in the medium amphibolite facies, whereas at the Insubric Line it just reaches the upper greenschist facies.

K-Ar cooling ages on white K-micas of about 20 m. y. have been determined for the mylonites north of the Insubric Line (ZINGG, et al., 1976), and further to the NE the onset of rapid cooling within the mylonites is supposed to be at about 23 m. y. (HURFORD, 1986). HURFORD presents different models of the cooling history after a Mid Tertiary peak of metamorphism (HUNZIKER, 1969; JÄGER, 1973). Since all visible deformations in the study area – apart from the local relics of probably pre-alpine deformation – seem to be related to only one temperature increase and decrease they should be related to this mid to late Tertiary thermal event. Within the study area we do not see any indication of an eoalpine event established for the southwest part of the Monte Rosa Nappe and of the Gneiss Zone, including the area around Val d'Ossola (DAL PIAZ et al., 1972; HUNZIKER, 1974). Moreover, the temperature distribution, established by this study, fits well the overall regional temperature distribution of the Lepontine region (as given by NIGGLI & NIGGLI, 1965).

Nevertheless, the possibility of an early alpine event "hidden" in the early stage of the first alpine deformation cannot absolutely be excluded. Detailed studies of microfabrics, especially of feldspar orientations (see KRUHL, 1987), are necessary to get better informations on strain orientation and sense of shear during the early alpine metamorphism and deformation.

In the Monte Rosa Nappe and the northern and central part of the Gneiss Zone the first and penetrative deformation has been outlasted by the annealing. Through that the regional distribution of the peak of metamorphism is – in addition to the oligoclase boundary and the chloritoid-staurolite transition – reflected by the diameters of recrystallized feldspar grains. Towards the Insubric Line the first deformation is active not only during increasing but also during decreasing temperatures, as it has been already shown by KRUHL (1979) in the area further towards the NE. Directly north of the Insubric Line a mylonite zone is developed during decreasing temperatures under conditions of greenschist facies. In contrast to SCHMID et al. (1987) we do not see any indications that the mylonitic foliation is not identic with the alpine s_1 further to the N. The third deformation shows a similar relationship to the temperature as the first one. In the northern part of the study area it occurs about at the peak of metamorphism whereas towards the Insubric Line the third deformation is more and more behind the maximum of temperature. At the Insubric Line the mylonitic foliation is refolded by the third deformation. Additionally, this deformation may be locally intensified and s_3 may be also developed as mylonitic foliation. Greenschist facies shear planes, occurring in the northern part of the Gneiss Zone and in the Monte Rosa Nappe, might well be procuded during a late stage of the third deformation.

In respect to the stretching directions, there are complications. Down-dipping and horizontal stretching lineations relieve one another in distinct parts of the Gneiss Zone and the Mylonite Zone, and they have most likely been developed at exactly the same metamorphic conditions as indicated by mineral parageneses and quartz fabrics. A synchronous development of the different stretching lineations might well be possible. Therefore – although there is ample evidence for dextral strike-slip movements, mainly near the Insubric Line but also further towards the NW (SCHMID et al., 1987) – we do not regard these movements as important as supposed by other authors (e. g. STECK, 1984; SCHMID et al., 1987) and not necessarily as a late event.

Despite the horizontal stretching lineations locally developed, we think that in general about vertical, or E-W directed movements respectively, have been active during the entire alpine event, as indicated by the majority of stretching lineations being roughly vertical from the first to the third deformation and, more precise, uplift of the Central Alps in relation to the Southern Alps at least during the third alpine event is indicated by the asymmetry of third folds.

In general, we consider the southern margin of the Central Alps between Val Loana and Val d'Ossola as an excellent example of the interaction between a continuous deformation and a temperature increase and subsequent decrease. The mylonization at the Insubric Line may have been forced by the decreased temperature as well as the decreased temperature may be a result of the mylonization and subsequent thrusting of the "hot" Central Alps over the "cold" Southern Alps. The overturned alpine temperature distribution and, additionally, the continuous deformation, accumulated at the Insubric Line during a late low temperature stage of metamorphism, support the idea of a continuous rotation and upward movement, bringing a pre-alpine gently SE dipping sequence continuously into the present overturned steeply NW dipping orientation.

The constitution of overall models on the geotectonic development at the southern margin of the Central Alps, as e. g. that stimulating one presented by SCHMID et al. (1987), are highly desirable but we think that the data, available at present, are not sufficient to provide a more or less satisfactory picture.

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