Zeitschrift: Schweizerische mineralogische und petrographische Mitteilungen = Bulletin suisse de minéralogie et pétrographie

Band: 66 (1986)

Heft: 1-2

Artikel: Structural and isotopic age profile across the Insubric Line, Mello, Valtellina, N. Italy

Autor: Wiedenbeck, Michael

DOI: https://doi.org/10.5169/seals-50892

Schweiz. mineral. petrogr. Mitt. 66, 211–227, 1986

Structural and isotopic age profile across the Insubric Line, Mello, Valtellina, N. Italy

by *Michael Wiedenbeck*[1]

Abstract

The northern Italian village of Mello, located on the northern side of the Valtellina valley, is situated on the Insubric Line. At Mello this fault is represented in the surface geology by a 300 to 500 meter wide, east-west trending zone of mylonites which separate the Central and Southern Alps. Relationships between the mylonites and their country rocks imply a complex tectonic history for the region; multiple deformation phases must be assumed for the fault, although only sub-horizontal mineral lineations have been found within the mylonites at Mello. Structural data clearly show that the mylonites represent a boundary between two zones with independent deformational histories. Foliation and mineral lineation orientations within the Insubric Mylonites are more closely related to those found in the more northerly Alpine aged Tonale Series than with those from the Southern Alps.

Hornblende and mica K/Ar and Rb/Sr ages show the presence of a late-Alpine metamorphism north of the Insubric Line. Ages within the Austroalpine Tonale Series span from 21 to 41 Ma. Dates from the yet more northerly Bergell Tonalite fall in the range from 23 to 29 Ma.

An attempt to determine the time of formation of the mylonites using the K/Ar and Rb/Sr muscovite systems gave non-reproducible ages. The processes involved in mylonitization are not necessarily sufficient to completely reset either of these isotopic systems. These data also indicate that a steep gradient exists between the mylonite zone and the Tonale Series in the intensity of the Alpine regional metamorphism.

A sample collected south of the mylonite zone yielded a pre-Hercynian K/Ar hornblende age, thus confirming the change in age of metamorphism across the mylonite zone.

Keywords: Insubric line, mylonites, deformation, isotopic ages, Alpine metamorphism.

Zusammenfassung

Das norditalienische Dorf Mello, Veltlin, befindet sich auf der Insubrischen Linie. In diesem Abschnitt besteht die Insubrische Linie aus einer 300 bis 500 m breiten, Ost-West gerichteten Zone aus duktil verformten Myloniten, die die Zentralalpen von den Südalpen trennt. Die Beziehung

[1] Department of Earth Sciences, Laboratory for Isotope Geochemistry, ETH-Zentrum, 8092-Zurich, Switzerland.

zwischen den Myloniten und ihren Nebengesteinen weist auf eine komplexe, mehrphasige Entwicklung hin, obwohl an Mineralien nur subhorizontale Streckungslineationen zu finden sind. Strukturdaten weisen deutlich darauf hin, dass die Mylonite eine Grenze zwischen zwei Zonen mit unabhängiger Strukturentwicklung sind. Die Orientierung von Schieferung und Lineationen in den Myloniten deutet darauf hin, dass die insubrischen Mylonite näher mit der nördlichen Tonale-Serie verwandt sind als mit dem südalpinen Grundgebirge.

Hornblende und Glimmer mit K/Ar- und Rb/Sr-Methoden bestimmt, zeigen, dass eine spätalpine Regionalmetamorphose nördlich der Insubrischen Linie stattfand. Proben aus der ostalpinen Tonale-Serie lieferten Alter zwischen 21 und 41 Mio. Jahren. Proben aus dem noch weiter nördlich gelegenen Bergell-Tonalit streuen zwischen 23 und 29 Mio. Jahren.

Ein Versuch, die Zeit der Verformung der Mylonite mit der K/Ar- und Rb/Sr-Methode an Muskovit zu bestimmen, hat keine reproduzierbaren Altersangaben geliefert. Die Vorgänge, welche zur Mylonitbildung führten, genügten vollständig, um diese Systeme zu verjüngen. Darüber hinaus deuten diese Daten daraufhin, dass ein sehr hoher Regionalmetamorphosegradient zwischen Mylonitzone und Tonale-Serie existiert.

Eine K/Ar-Hornblende-Messung einer Probe aus den Südalpen ergab ein präherzynisches Alter und bestätigt, dass der Alterssprung der Regionalmetamorphose im Bereich der Mylonitzone liegt.

Riassunto

Il villaggio di Mello, sul versante Nord della Valtellina nell'Italia settentrionale si trova sulla linea Insubrica. In questa regione la linea Insubrica affiora in una zona di miloniti deformate plasticamente, estendentesi da est ad ovest, larga da 300 a 500 metri, che separa le Alpi centrali dalle Alpi meridionali. I rapporti fra miloniti e rocce contigue implicano una evoluzione tettonica molto complessa, comprendente più fasi, sebbene nei minerali rinvenuti nelle miloniti di Mello siano riconoscibili solo lineazioni di minerali suborizzontali. Dai strutturali si desume chiaramente che le miloniti rappresentano una fascia di separazione fra due zone dalla evoluzione strutturale indipendente. Le orientazioni della foliazione e della lineazione nelle miloniti insubriche sono più simili a quelle trovate nella serie del Tonale, che non a quelle nelle Alpi meridionali.

A nord della linea Insubrica, orneblenda e mica, datati con i metodi K/Ar e Rb/Sr, mostrano un metamorfismo tardo-alpino. Campioni della serie austroalpina del Tonale hanno età comprese fra 21 e 41 m.a.; quelli provenienti dalla tonalite della Bregaglia, poco più a nord, fra 23 e 29 m.a.

Un tentativo di datare l'evento della formazione delle miloniti con il metodo K/Ar e Rb/Sr sulla muscovite non ha dato risultati riproducibili: i processi implicati dalla milonitizzazione non sono sufficienti ad azzerare completamente questo orologio geocronologico. Questi dati indicano inoltre un forte gradiente nell'intensità del metamorfismo regionale alpino fra la zona delle miloniti e la serie del Tonale.

Un campione delle Alpi meridionali datato pre-ercinico con il metodo K/Ar sull'orneblenda, conferma il cambiamento dell'età del metamorfismo regionale attraverso la zona delle miloniti.

Introduction

This study of the structural and geochronological history of the Insubric Line was based around the northern Italian village of Mello (46 10'N; 9 32'E) (see Fig. 1). The goal of this work was to investigate variations in field structural

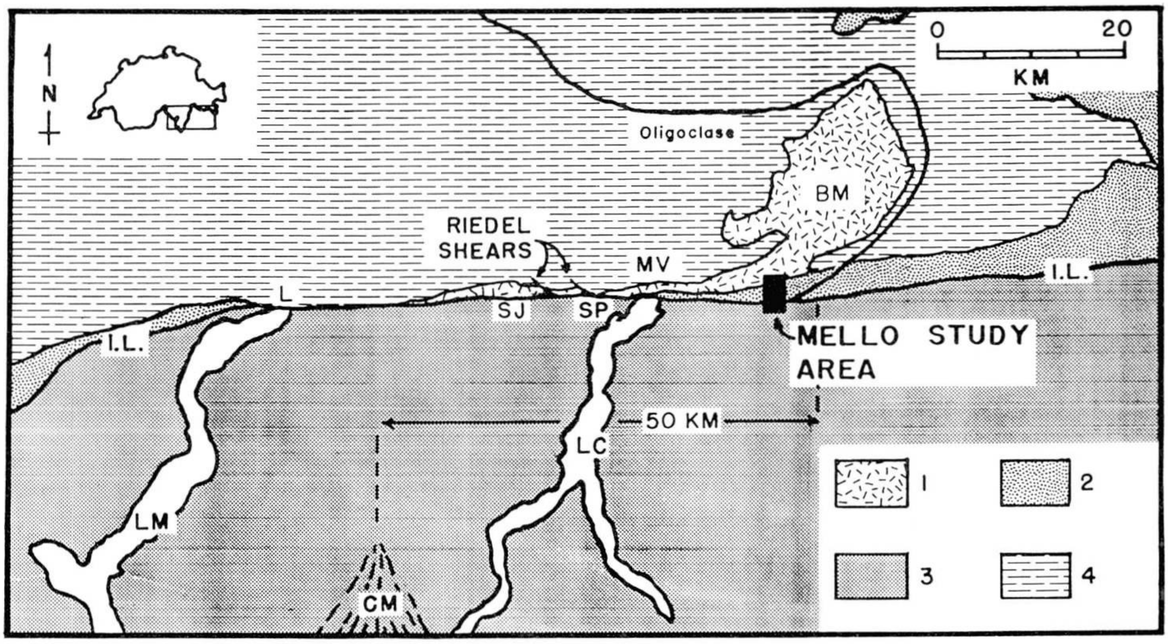

Fig. 1 Map showing the regional geology around the Mello study area. Included on the map is the mineral zone isograd boundary for the first appearance of oligoclase (WENK, 1970) for the Alpine aged Lepontine regional metamorphic terrain. Also shown is the location of the Bergell Tonalite cutting Riedel Shears and the 50 kilometer east-west offset between the Como Molasse and the present day position of the Bergell Complex (FUMASOLI, 1974) discussed in text. Legend: 1 = Bergell instrusives, 2 = Austroalpine nappe sequence, 3 = Southern Alps, 4 = Pennine nappe sequence, I.L. = Insubric Line, SP = Sasso Pelo dolomite, MV = Mera Valley, SJ = San Jorio Pass, BM = Bagni del Masino, CM = Como Molasse, L = Locarno, LC = Lake Como and LM = Lake Maggiore.

data and K/Ar and Rb/Sr isotopic dates with respect to their position relative to the Insubric fault zone. Work on the geology of Mello was conducted in two phases: first an area of 10 km^2 was mapped in detail for surficial geology while at the same time collecting structural data from across the area. Secondly, six large samples were collected for laboratory dating using the K/Ar and Rb/Sr methods on hornblende and mica. Site selection was based on the completeness of continual section perpendicular to the local east-west trending geological structures. One major advantage of the Mello area was that it offered within a north-to-south traverse distance of only 2.5 km four different tectonic units (see Fig. 2):

1. The Bergell Tonalite (an Alpine intrusive).
2. The Tonale Series (a heterogeneous group of schists belonging to the Austro-Alpine nappe sequence).
3. The Insubric Mylonites (a ductilly deformed fault material derived primarily from Tonale Series rocks).
4. The Morbegno Gneiss (regionally metamorphosed rocks of the Southern Alps).

The main disadvantage of the Mello area was the low outcrop level. The area has been widely covered by Quaternary deposits. Thick vegetation along with

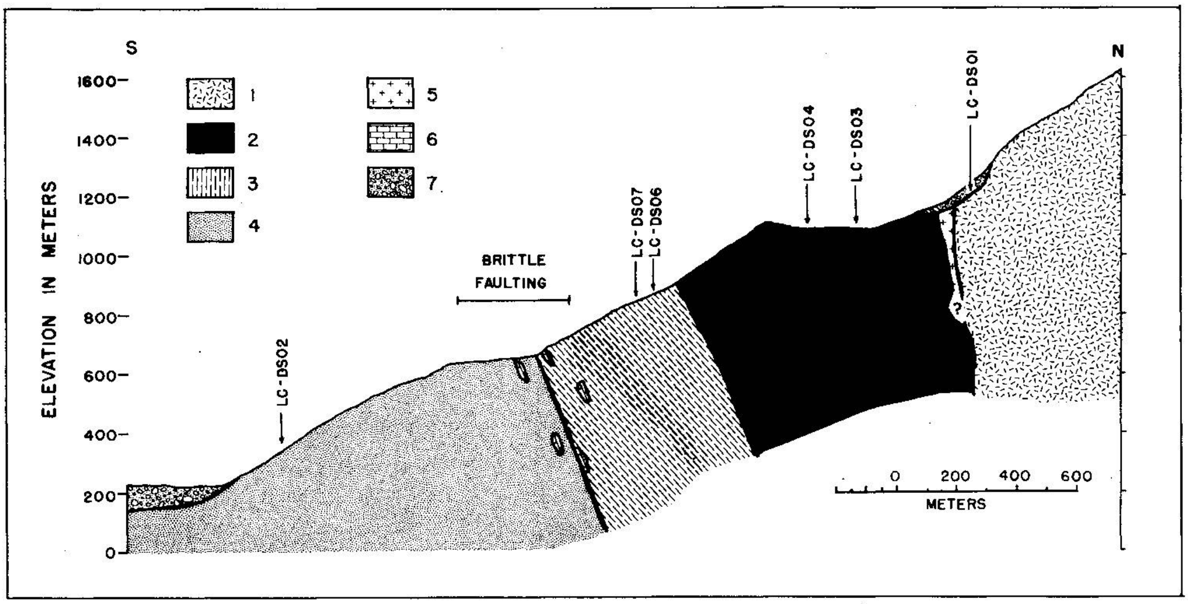

Fig. 2 North–south geologic cross-section through the Mello area showing the relationships between the four major tectonic units. The direction of the shading within the mylonite zone (the second most southern unit) indicates the average dip of this unit. Relative locations of the samples used for isotopic age dating are given by their sample numbers. Also shown are the area of brittle faulting and the position of the Melirolo Augen Gneiss. The nature of the contacts between the various units, and particularly so for the carbonate lenses, are uncertain with the exception of the Melirolo Augen Gneiss which has a sharp contact with the Tonale Series schists (see Fig. 3). Legend: 1 = Bergell Tonalite, 2 = Tonale Series, 3 = Insubric Mylonites, 4 = Morbegno Gneiss, 5 = Melirolo Augen Gneiss, 6 = Carbonates and 7 = Quaternary Cover. No vertical exaggeration.

agricultural cultivation have further reduced the number of outcrops. The majority of the outcrops are confined to stream beds and along roadsides, though sporadic bedrock outcrops are found elsewhere.

The Insubric Line

The Insubric Line is the most visible tectonic lineament of the Alps, extending from northwestern Italy to Austria over a distance of some 400 km. In the area around the village of Mello this structure represents the boundary between the Central and Southern Alps. To the north of the Insubric Line deformation is primarily Alpine in character, including the classical nappe structure of the Swiss Alps. To the south of the line structures are predominantly pre-Alpine. Another important feature of this segment of the Insubric Line is that the age of the regional metamorphism changes from Alpine in the north to Hercynian or pre-Hercynian in the south.

The history of the Insubric Line is complex, both dip-slip and dextral strike-slip motions have taken place (Schmid et al., 1986). An estimate of the amount of vertical displacement which has taken place on the Insubric Line is given by the change in grade of regional metamorphism across the mylonite zone. The sudden change in the degree of Alpine metamorphism from amphibolite grade to the north to non-metamorphic/anchi-metamorphic to the south is evidence of an 20–25 km uplift of the northern block relative to the southern (BÜCHI and TRÜMPY, 1976). Combined with the northern dip of the foliation of the mylonites this is evidence for a compressional high angle reverse thrusting event (backthrusting) as being responsible for the termination of the Alpine Tertiary regional metamorphism.

The sub-horizontal mineral lineations in the mylonites at Mello indicate the presence of a strike-slip displacement. The lack of vertical lineations is presumably due to a complete overprinting by later horizontal motions within the mylonites. Lineation measurements from within the mylonites west of Locarno, some sixty kilometers west of Mello, have shown that the vertical motions on the Insubric Mylonites pre-date and are independent of the horizontal strike-slip movements (SCHMID et al., 1986).

Field evidence also indicate a south-block-up displacement along the Insubric Line. This conclusion is based on the fact that at the northern end of Lake Como the Mesozoic Sasso Pelo dolomite, the sedimentary cover of the Southern Alpine basement, steepens in dip as it approaches the mylonite zone from the south—an indication of drag folding (FUMASOLI, 1974). The significance of this event is not clear.

The absolute ages of the various phases of Insubric deformation may be constrained by both isotopic age data and field observations. Since the mylonites represent the southern boundary of the Alpine regional metamorphism (see Fig. 1), the onset of uplift of the Lepontine region represents an upper (older) limit for the beginning of the vertical motions within the mylonites. HURFORD (1986), applying a strict blocking temperature concept, estimated that uplift of the central Lepontine zone began around 23 Ma ago. Furthermore, the presence of material derived from the Bergell complex in the Como Molasse gives another indication of the timing of movements on the Insubric Line. Micropalaeontological stratigraphy has shown that Bergell boulders were deposited in an deep-sea fan environment between middle to late Oligocene and latest Oligocene (RÖGL et al., 1975). This means that at least part of the Bergell intrusion was undergoing erosion around 23 to 27 Ma ago. These numbers may be taken as absolute values for the lower limit for the onset of uplift of the Bergell region. Assuming an intrusion age for the "Bergell Granite" of 30.3 Ma (GULSON and KROGH, 1973), it may be concluded that the Bergell Massif soon thereafter underwent rapid uplift, possibly reflecting high strain rates around 25–30 Ma within the bordering Insubric Mylonites.

As mentioned above, the horizontal movements in the Insubric Mylonites post-date the high angle reverse (backthrusting) phase. A definite upper limit of the termination of the strike-slip displacement may be made based on Insubric deformation which is within the Bergell Tonalite. Field mapping of the area between San Jorio pass and Lake Como showed that riedel shears, related to a dextral strike-slip displacement on the Insubric Line, cross-cut the Bergell Tonalite (see Fig. 1) (FUMASOLI, 1974). This means that this deformation must have, at least in part, taken place after the solidification of the tonalite. Taking the 32.0 Ma K/Ar hornblende age (DEUTSCH and STEIGER, 1985) as the time of emplacement of the tonalite, then strike-slip movements must have taken place after this point in time. It is also possible to estimate the absolute amount of this post-tonalite dextral motion, a value which has been set at 50 kilometers. This value is based on the east-west distance between the location of the Como Molasse south of the Insubric Line and the modern day position of the Bergell complex (see Fig. 1).

The time of termination of motions on the Insubric system is inaccurately known. The oldest geologic formations which have not been affected by the fault are Pleistocene glacio-fluvial deposits. This is a lower (younger) limit of the ending of the motions on the Insubric Line. The morphology of the drainage system suggests that both Lake Como and Lake Maggiore, both having eastward bends at their northern ends, may have existed prior to the termination of the last strike-slip motions.

The Bergell Massif

The Insubric Line is not only of tectonic but also of petrologic significance. A relationship seems to exist between this fault system and the location of Alpine aged plutonism. Essentially all Alpine plutons are concentrated within a small distance either north or south of the fault zone. One of the largest of these "Insubric plutons" is the Bergell complex, a multi-phased, late Alpine intrusive, dominated by tonalitic, granodioritic and granitic phases. One of the major problems in deciphering the history of the Bergell Massif is the question of the origin of the deformation seen within the complex. Weak to sometimes strong foliations may be seen at many locations in both the tonalite and the granodiorite. Arguments to support that the foliation is either tectonic or flow-banding in origin have both appeared in the literature (MOTICSKA, 1970; WENK, 1973; TROMMSDORFF and NIEVERGELT, 1983). At least some of the foliation which is seen in Bergell is certainly related to a tectonic overprinting. In the Mera valley isoclinally folded quartz veins with strong axial planar schistosities are visible within the tonalite. HEITZMANN (1974) has reported the existence of tonalitic veins which have been folded around axial planes parallel to pre- or syn-intrusive schistosities. On San Jorio Pass axial ratios of xenoliths from within the tonalite have been used to show the presence of large amounts of flattening in this area (VOGLER and VOLL, 1976; 1981). A tensional phase has also been shown to have affected the Bergell Tonalite. Tonalitic veins within the meta-sedimentary country rocks northeast of the massif have been stretched into boudins (BUCHER-NURMINEN, 1977). How all of these different deformational phases are related to each other is unknown. All that is certain is that the Bergell complex underwent deformation subsequent to its solidification.

Another, as yet unsolved issue concerning the Bergell Massif is the relationship between the contact metamorphism induced at the time of emplacement and the late-Alpine regional metamorphism which is also present in the area. Field evidence shows the presence of a contact metamorphic aureole at the eastern margin of the pluton which has overprinted an earlier regional metamorphic event (GAUTSCHI, 1980). Along the western margin of the Bergell Massif no contact metamorphic mineral assemblage zones are seen (MOTICSKA, 1970). When mineral isograd patterns for the Lepontine regional metamorphism are drawn they are therefore generally sketched to pass very close to the eastern and southern margins of the Bergell intrusives (see Fig. 1). It is this difference in the nature of the metamorphism between east and west which has led TROMMSDORFF and NIEVERGELT (1983) to postulate a minimum of 8 km of post-intrusion east-west differential uplift in order to explain the change in style of metamorphism across the Bergell complex.

One further peculiarity of the Bergell Massif is the presence along much of the southern margin of the tonalite of a distinct lithologic unit: the Melirolo Augen Gneiss (see Fig. 2). The presence of this marginal facies, interpreted by VOGLER and VOLL (1981) as being a sub-volcanic intrusive, has long been known further to the west between San Jorio pass and the Mera valley. This narrow zone of often strongly foliated rock has now also been located in the Mello area. Perhaps more important than its simple existence is the observation that the foliation of the augen gneiss at Mello is sub-discordant to its country rock (see Fig. 3). The foliation in the Melirolo Augen Gneiss may therefore be attributed to a postemplacement tectonic overprinting.

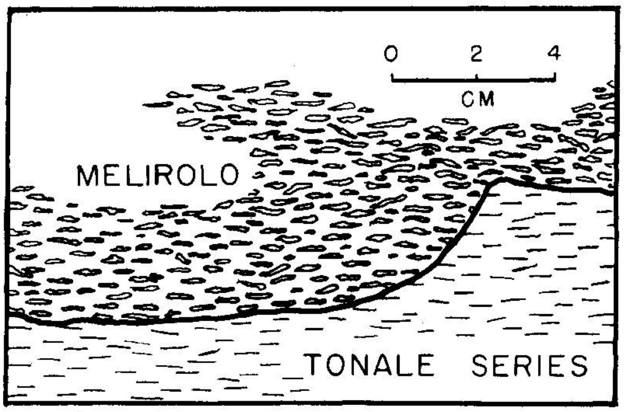

Fig. 3 Sketch of the field relationships at the southern contact of the Melirolo Augen Gneiss (Swiss grid coordinates 761.6/114.7). An east-west (right to left) trending foliation is seen in both the augen gneiss (top) and a quartzite gneiss of the Tonale Series (bottom). Note how the foliation, indicated by the feldspar augens in the Melirolo unit and by the orientation of mica grains in the Tonale Series, cross-cuts the contact between the two lithologies.

Field Mapping

In the field the Insubric Mylonites proved to be a highly heterogeneous rock series. Rapid variations in both the lithologies and the intensity of mylonitization were common through the mylonite zone (see Fig. 4). Due to the similarities in the lithologies north and south of the mylonite zone—mica schists predominating—it was often difficult to determine with which of these two series a particular mylonite outcrop was more closely related, though it appears that the majority of the material is more closely related to the Tonale Series than with the Southern Alps. Mapping also revealed the presence of brittle deformation in the southern-most third of the mylonite zone and the adjoining portions of the Morbegno Gneiss (see Fig. 4). This is an important point, that the brittle faulting (the "Tonale fault line") is an independent, post-mylonite deformation which is also seen south of the mylonite zone.

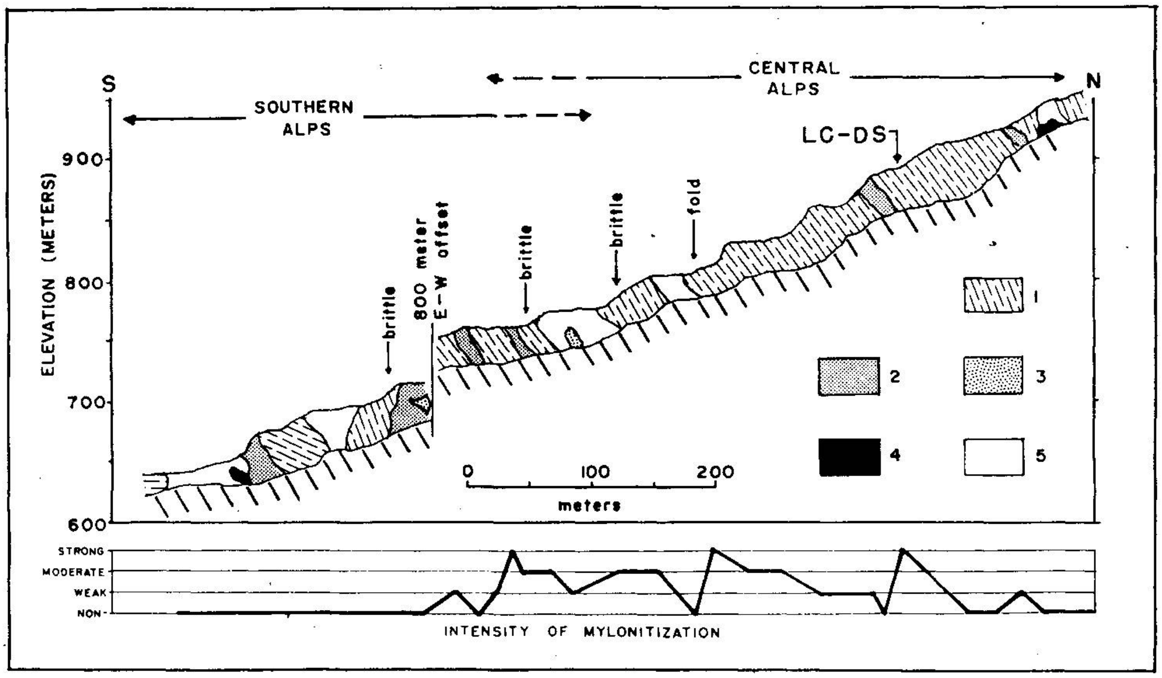

Fig. 4 North-south stream profile through the Insubric Mylonite zone east of the village of Mello. Indicated by arrows at the top is the region from which the material in the mylonite zone appear to have been derived. At the bottom of the figure is a graph of position against the subjectively determined intensity of mylonitization (strong, moderate, weak and non-mylonitic). Zones of brittle deformation and the location of an intra-mylonitic, recumbent isoclinal fold are also shown. The orientation of the shading of the gneisses reflects the local average dip. Legend: 1 = mica schists, 2 = quartzites, 3 = carbonates, 4 = amphibolites and 5 = covered zones. LC-DS indicates the position from which the two isotopic age dating samples were collected. No vertical exaggeration, although the hight of the profile has been expanded for clarity.

Near the contact between the mylonite zone and the Morbegno Gneiss occasional isolated outcrops of carbonates are present (see Figs. 2 and 4). South of the mylonites these materials are clearly sedimentary in origin, suggesting that these carbonates are part of the Mesozoic cover sediments of the Southern Alps.

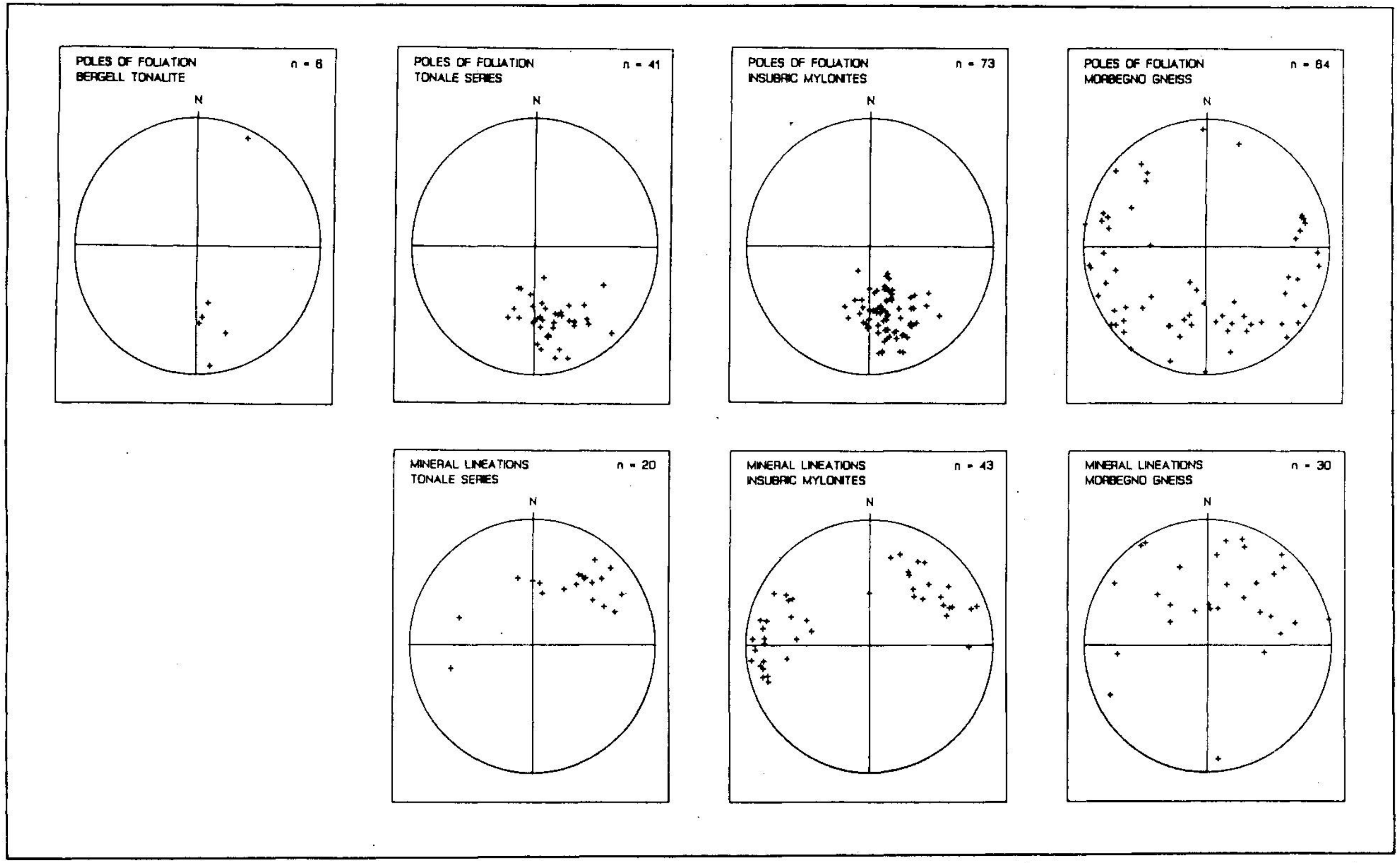

Fig. 5 Stereo-net plots for the field structural orientations collected from the Mello area. The plots are of the lower hemisphere of an equal area projection. The letter "n" represents the number of data points plotted in each projection.

Carbonates located within the mylonites have often been deformed, attested to by intensely twinned calcite grains. These are presumed to be mylonitized equivalents of the Southern Alpine sediments.

The structural field data collected from the area showed that distinct strain patterns could be assigned to each of the four tectonic units: the Bergell Tonalite, the Tonale Series, the Insubric Mylonites and the Morbegno Gneiss. The northern most of the four tectonic units, the Bergell Tonalite, often appeared massive, possessing no structural orientation or only weakly defined foliations. Lineations are rare in the Tonalite. The stereo-net representations of the structural data collected from the Tonale Series show a very strong clustering (see Fig. 5). Throughout the area only a single, moderately north-northwesterly dipping foliation was found. The mineral lineations from the Tonale Series were also highly regular, plunging moderately to the northeast. In the third tectonic unit, the 300–500 meter wide mylonite zone, a foliation is visible which is nearly identical to that seen in the Tonale Series. The orientations of the mineral lineations are also remarkably similar, except that in the Insubric Mylonites an additional grouping of westward sub-horizontal plunging lineations is also present. From the available data it is not possible to decide between two possible interpretations of the lineation data from the mylonite zone:

1. The lineations in the mylonites are due to a single event in which stress orientations were highly variable in time or space.
2. The lineations in the mylonites are the result of two phases of deformation, one involving the mylonite zone only (west plunging) and a second one which also expressed itself in the more northerly Tonale Series (northeast plunging).

An important observation is that the mineral lineations seen in the mylonite zone do not vary with geographical location, which would argue for the first of the two options given above (see Fig. 6). In the southern most tectonic zone, the Southern Alpine Morbegno Gneiss, structural patterns are apparently unrelated to those farther to the north. Dips were generally northward, though no clustering of orientations could be found. From the structural data collected there appears to be no relationship between the structures seen south of the Insubric Line and those seen in the mylonites and farther to the north.

Sample Preparation and Analysis

Sample characteristics and site locations are given in Table 1. Rock samples for isotopic analysis were crushed followed by the preparation of high-purity mineral separates using standard techniques (magnetic, heavy liquid and vibrating platform methods). Finally, handpicking was conducted in order to obtain the maximum possible purity of the mineral concentrates. Radiogenic

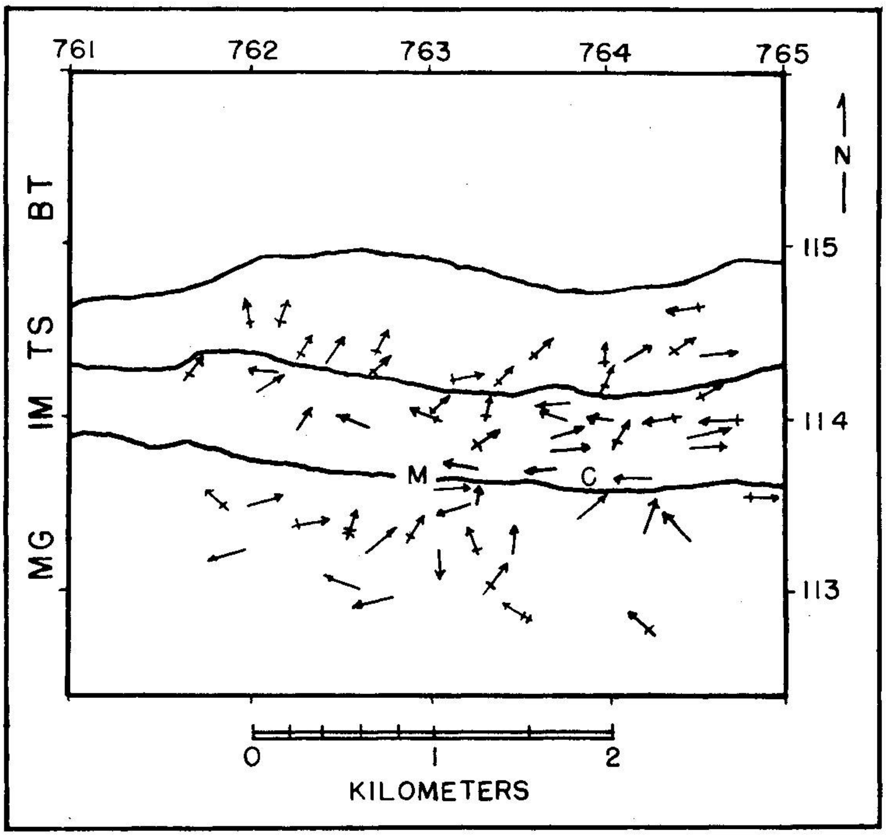

Fig. 6 Tectonic sketch map showing the orientations of the mineral alignment lineations. The heavy black lines represent the traces of the contacts between the various tectonic units. The arrows indicate the trend of the mineral lineations measured in the field. Plung of the lineations is indicated by the number of crosshatches: no hatches = 0–30, 1 hatch = 30–60, 2 hatches = 60–90. Legend: BT = Bergell Tonalite, TS = Tonale Series, IM = Insubric Mylonites, MG = Morbegno Gneiss, M = village of Mello and C = village of Civo. Swiss metric grid coordinates are indicated.

argon concentrations were determined by the peak height method without the use of an argon tracer. Argon extraction took place by total fusion of mineral grain samples at 1700 °C followed by purification in an all-metal gas extraction line.

Potassium, rubidium and strontium concentrations and isotopic compositions were determined by isotope dilution and mass spectrometric techniques.

Tab. 1 Table giving the lithologies and locations (Swiss grid coordinates) of the samples studied for mineral isotopic ages. The mineral abbreviations are: bio = biotite, ep = epidote, hbl = hornblende, feld = feldspar, chl = chlorite and gnt = garnet. Mineral names appearing in upper case letters were those analysed for their isotopic ages. Mineral components are listed in the sequence of from most to least common.

SAMPLE	UNIT	ROCK TYPE	COORDINATES	TOTAL MASS (kg)
LC-DS01	Bergell Tonalite	BIO-ep-HBL Tonalite	761.24/114.78	16.
LC-DS02	Morbegno Gneiss	HBL-feld Amphibolite	764.30/112.77	13.7
LC-DS03	Tonale Series	HBL-feld Amphibolite	764.47/114.69	14.2
LC-DS04	Tonale Series	MUS-BIO-chl Gneiss	764.35/114.54	12.3
LC-DS06	Insubric Mylonites	MUS-bio-gnt Mylonite	763.64/114.07	16.7
LC-DS07	Insubric Mylonites	MUS-bio-gnt Mylonite	763.64/114.01	22.3

In the cases where data for all three elements—potassium, rubidium and strontium—were desired for the same material, only a single sample aliquot was used. Separate, independent grain splits were used to determine the radiogenic argon concentrations.

Tables 2 and 3 give the isotopic age results. All data were calculated based on the decay constants recommended by the IUGS Subcommission on Geochronology (STEIGER and JÄGER, 1977). The errors cited represent 95% confidence limit precision estimates. Both the errors for K/Ar and Rb/Sr are based on error propagation taking into account the uncertainties in mass spectrometer precision and isotopic blanks. For argon data further factors involving sample inhomogeneity (assumed not to have exceeded 2%) and corrections for non-radiogenic components within the sample were also included in the estimates of data accuracy. Argon data have not been corrected for deviations in the measured values of interlaboratory standards. Eleven runs of the hornblende standard MMhb-1 (an Ordovician bentonite) gave average radiogenic ^{40}Ar concentrations of 1.595 ± 0.014 nmol/g, or approximately 2% below the value obtained from averaging the results from nine different laboratories (from personal communications from Dr. S. D. Samson, University of Minnesota, USA).

Age Dating

From a single sample of the Bergell Tonalite, LC-DS01, a hornblende K/Ar age along with biotite K/Ar and Rb/Sr ages were obtained (see Table 1 for brief descriptions). For the hornblende K/Ar age a single split was measured for its radiogenic ^{40}Ar concentration, while a second split was used to determine the potassium concentration. For this particular sample of hornblende a relatively imprecise age of 28.8 ± 2.2 Ma was obtained, this being due to large corrections for an elevated atmospheric argon contribution. When compared with the hornblende age from the center of tonalite at Bagni del Masino of 32.0 ± 1.2 Ma (DEUTSCH and STEIGER, 1985) the values marginally overlap. If this overlap is real cannot be shown with the data available here. Biotite separated from the same sample produced a K/Ar age of 23.6 and a Rb/Sr age of 23.5 Ma. These values correspond well to the ages which have been measured in the region using these same mineral-isotope systems (JÄGER et al., 1967; WAGNER et al., 1977).

Two samples were collected from the Tonale Series, the first from an amphibolite lense (LC-DS03), the second from a biotite-muscovite schist (LC-DS04). The data collected from these samples clearly show an Alpine affinity for the Tonale Series. A K/Ar age of 40 Ma was obtained from metamorphic hornblende in sample LC-DS03. This age is difficult to interpret in that it does

Tab. 2 Argon isotopic analysis table. Potassium concentrations obtained from isotopic dilution/mass spectrometer analysis are assumed to have a maximum precision of 98% (2 sigma) so as to compensate for possible sample inhomogeneity. Repeat argon analyses appear in the list directly after each other. Weights indicated are those of the mineral splits which were fused in order to determine argon composition. Errors given in the calculated age represent the 95% confidence level.

SAMPLE NUMBER	MATERIAL	MINERAL	GRAIN SIZE [MICRONS]	K [%]	AR36 [IN UNITS 10^{-8} cc/g]	AR38	AR40	RADIOGENIC AR 40 [10^{-8} cc/g]	AR40 [%RAD]	WEIGHT [MG]	CALCULATED AGE [MY]
LC-DS01	Bergell Tonalite	Hornblende	100 - 315	1.26	3.533	.660	1186.	142.+- 11.	12	21.4	28.8+- 2.2
LC-DS01	Bergell Tonalite	Biotite	100 - 315	7.77	.688	.1286	919.	715.+- 5.	78	9.7	23.5+- 0.5
				7.77	.829	.1559	962.	717.+- 6.	75	9.1	23.6+- 0.5
LC-DS02	Morbegno Gneiss	Hornblende	50 - 150	0.38	.471	.0883	749.	609.+- 4.	81	13.5	373.+- 7.
				0.38	7.20	1.368	2711.	582.+- 23.	21	5.5	358.+- 14.
LC-DS03	Tonale Series	Hornblende	160 - 275	0.59	.2066	.03859	155.5	94.5+- 1.0	61	18.2	40.8+- 0.9
				0.59	.1231	.02302	127.7	91.3+- 0.8	72	41.6	39.5+- 0.8
LC-DS04	Tonale Series	Muscovite	180 - 315	6.71	.986	.1834	957.	666.+- 6.	70	4.4	25.4+- 0.5
				6.71	.582	.1081	837.	664.+- 5.	79	8.6	25.3+- 0.5
LC-DS04	Tonale Series	Biotite	180 - 315	7.31	.845	.1584	933.	683.+- 6.	73	6.0	23.9+- 0.5
				7.31	.598	.1121	866.	689.+- 5.	80	10.9	24.1+- 0.5
LC-DS06	Insubric Mylonite	Muscovite	200 - 315	8.03	.907	.1675	3654.	3386.+- 19.	93	4.2	105.4+- 2.1
LC-DS07	Insubric Mylonite	Muscovite	200 - 315	7.86	1.321	.2447	2308.	1917.+- 1.3	83	8.6	61.8+- 1.3

Tab. 3 Rubidium/strontium isotopic analysis table. Ages given in the final column represent the value for the regression line through the mineral and corresponding whole rock data point. All precision values cited are for the 95% confidence level.

SAMPLE	MATERIAL	MINERAL	GRAIN SIZE [MICRONS]	Rb [ppm]	Sr [ppm]	86Sr [10^{-8} mol/g]	87Rb/87Sr	87Sr/86Sr	AGE [my]
LC-DS01	Bergell Tonalite	Whole Rock		88.374	265.30	29.8502	0.964188	0.71206+-0.00008	
LC-DS01	Bergell Tonalite	Biotite	100 - 315	411.01	8.2327	0.921961	145.183	0.76017+-0.00039	23.5+-0.5
LC-DS01	Bergell Tonalite	Hornblende	100 - 315	23.002	22.894	2.57584	2.90819	0.71251+-0.00018	16.4+-9.4
LC-DS04	Tonale Series	Whole Rock		139.36	277.18	31.1373	1.45755	0.72819+-0.00010	
LC-DS04	Tonale Series	Biotite	180 - 315	531.05	10.715	1.19868	144.282	0.77144+-0.00016	21.3+-0.4
LC-DS04	Tonale Series	Muscovite	180 - 315	149.03	159.28	17.8926	2.71265	0.72871+-0.00006	29.+-10.
LC-DS06	Insubric Mylonite	Whole Rock		127.47	202.66	22.7774	1.82252	0.72343+-0.00006	
LC-DS06	Insubric Mylonite	Muscovite	0 - 315	179.95	144.31	16.2121	3.61491	0.72927+-0.00034	220.+-22.
LC-DS07	Insubric Mylonite	Whole Rock		83.042	232.19	26.1059	1.03595	0.71982+-0.00046	
LC-DS07	Insubric Mylonite	Muscovite	200 - 315	157.18	145.25	16.3221	3.13624	0.72503+-0.00023	174.+-26.

not fit the pattern for the rest of the Mello area. There are three possible interpretations for this 40 Ma date:

1. The date reflects a real event.
2. The date represents a mixed age due to incomplete resetting of a pre-Alpine hornblende during a post-40 Ma regional metamorphism.
3. The date is the result of partial argon loss during the contact heating at the time of emplacement of the Bergell Tonalite.

Support for the interpretation that a real event affected the Tonale Series around 40 Ma ago is provided by STEINITZ and JÄGER (1981) who found, based on Rb/Sr phengite—whole rock data, that a metamorphic event took place in the Suretta Nappe between 35 to 40 Ma ago. Their study area was located 35 km north of Mello. In order to demonstrate that the 40 Ma event in the Tonale Series is real, it would be necessary to collect additional samples of hornblende from the Tonale Series for K/Ar analysis, thereby showing that the age is reproducible. Support for the second interpretation, that of a partial resetting during a yet younger event, is provided by DEUTSCH and STEIGER (1985) who showed that hornblende ages on the periphery of the Lepontine metamorphic zone are frequently only partially reset. The third hypothesis (contact heating) seems the least likely. This conclusion is based on work by HART (1964) which shows that thermal resetting of the K/Ar hornblende system is not significant more than a few meters away from the contact of a granitic intrusive.

The data collected from mica in the Tonale Series fit well into the regional pattern. In accordance with the blocking temperature concept (see HURFORD, 1986), white mica yielded older ages than biotite. Close agreement is seen between the biotite Rb/Sr age with the data from the tonalite. At this time it is not possible to explain the ca. 10% difference in the K/Ar and the Rb/Sr biotite ages measured for the Tonale Series.

One of the main goals of this study was to determine the absolute age of the formation of the Insubric Mylonites. White mica, being the only component of the mylonites which was coarse enough to allow for mineral separation, did not provide geologically meaningful ages. K/Ar and Rb/Sr dates on large white micas from two different samples (LC-DS06 and LC-DS07) gave four statistically resolvable ages (see Fig. 7). This scatter in ages could be due to two different causes; either the thermal and deformational effects of mylonitization only produced a partial resetting, or the samples which were separated were composed of a mixture of old micas and ones which had been totally recrystallized during the mylonitization process. In either case, the process of mylonitization is not alone sufficient to reset either the K/Ar or Rb/Sr white mica systems. This conclusion, if strictly applied to a blocking temperature concept, argues that the temperature of the mylonites never exceeded the 380 °C K/Ar musco-

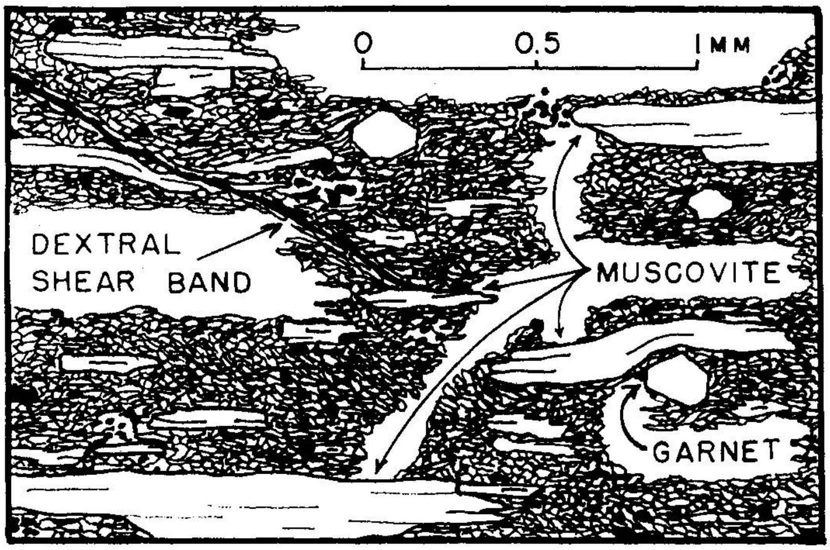

Fig. 7 Schematic thin section view of a typical ultra-mylonite sample. Such large, clear muscovite grains as are scattered throughout the view were separated for isotopic dating. The matrix consists of quartz and feldspar (equant grains), biotite and fine grained muscovite (elongate) and ore minerals (opaque). In certain regions of the mylonite zone garnets are also present (large, equant grains in sketch) which typically induce an asymmetrical geometry in the surrounding foliation. Note the strong foliation which is defined by the orientation of the micas. A shear band, having the typical dextral offset, is also shown.

vite blocking temperature during Alpine times (JÄGER, 1973). Mylonitization must therefore have taken place below this temperature. Another, and perhaps more significant conclusion is that the material of which the mylonites are composed never saw elevated temperatures during the Alpine Lepontine metamorphism. Though the materials in the mylonite zone are predominantly derived from the Tonale Series (particularly so in the north where the samples were collected), the protolith of the mylonites could not have been juxtaposed to their modern day country rocks at the time of the regional metamorphism. A relative movement must therefore have taken place between the Tonale Series and the protoliths of the Tonale Series derived mylonites since the termination of the Lepontine regional metamorphism. This relative motion is perhaps related to a dragging-in mechanism involving (strike-slip?) motions within the mylonite zone.

A single amphibolite sample (LC-DS02) was collected from the fourth tectonic unit, the Morbegno Gneiss. A K/Ar analysis of hornblende from this sample gave an age of around 360 Ma. Based on data from MCDOWELL (1968a; 1968b), this date is interpreted as representing a mixing of a Caledonian event between 390 and 440 Ma with a Hercynian overprinting around 315 Ma. This conclusion is based on the assumption that excess argon did not play a significant role in the sample which was analysed. No evidence of Alpine thermal activity south of the mylonite zone was found.

Conclusion

Structural data collected in the field clearly show that each of the four tectonic units which are present in the Mello area has undergone its own, unique deformational history. The data collected show that a structural relationship exists between the Insubric Mylonites and the more northerly Tonale Series. This relationship could only have been induced after the two units had been placed adjacent to each other in their current relative positions. No structural relationships were found between the mylonites and the Southern Alpine Morbegno Gneiss.

Isotopic ages from the Mello area have confirmed the presence of an age jump across the mylonite zone from late-Alpine in the north to pre-Alpine south of the mylonites. Isotope data from the mylonite zone itself show that these materials never experienced elevated temperatures during the Alpine Lepontine regional metamorphism. A very high gradient in the grade of Alpine regional metamorphism exists between the mylonites and the Tonale Series schists as they are positioned today.

Acknowledgements

This paper represents the data resulting from a Diploma thesis project conducted between April 1983 and December 1984. The laboratory work presented here was conducted at the Laboratory for Isotope Geochemistry at the ETH-Zurich. I am grateful to all of the members of this institute who have provided so much assistance, making this project possible, and in particular for their readiness to explain the workings of the machines and the philosophies behind isotopic age determination. Particular mention goes to M.T. Bär, H. Baur, I. Ivanov, M. Meier and F. Oberli. Prof. R.H. Steiger and Dr. S. Schmid, both of the ETH-Zurich, were advisors for this project to both of whom I am thankful for their ideas concerning both field geology and the interpretation of the ultimate laboratory data.

Personal financial support for the period of this study was covered by a stipendium from the Swiss federal government. Additional financial resources were provided by the Laboratory for Isotope Geochemistry.

References

BUCHER-NURMINEN, K. (1977): Die Beziehung zwischen Deformation, Metamorphose und Magmatismus im Gebiet der Bergeller Alpen. Schweiz. mineral. petrogr. Mitt., 57/3, 413-434.

BÜCHI, U.P. and TRÜMPY, R. (1976): Bemerkungen zum geologischen Profil längs der Geotraverse Basel-Chiasso. Schweiz. mineral. petrogr. Mitt., 56, 589-603.

DEUTSCH, A. and STEIGER, R.H. (1985): Hornblende K-Ar ages and the climax of Tertiary metamorphism in the Lepontine Alps (south-central Switzerland): an Old Problem Reassessed. Earth Plan. Sci. Let., 72, 175-189.

FUMASOLI, M.W. (1974): Geologie des Gebietes nördlich und südlich der Jorio-Tonale-Linie im Westen von Gravedona (Como, Italia). Ph. D. dissertation, University of Zurich, 230 p.

GAUTSCHI, A. (1980): Metamorphose und Geochemie der basischen Gesteine des Bergeller Ostrands. Ph. D. dissertation, ETH-Zurich, 170 p.

GULSON, B.L. and KROGH, T.E. (1973): Old lead components in the young Bergell Massif: South-East Swiss Alps. Cont. Min. Pet., 40, 239-252.

HART, S.R. (1964): The petrology and isotopic-mineral age relations of a contact zone in the Front Range, Colorado. Jour. Geol., 72, 493-525.

HEITZMANN, P. (1974): Die «Wurzelzone» zwischen Valle di Livo und Lago di Mezzola (Provincia di Como, Italia). Ph. D. dissertation, ETH-Zurich, 137 p.

HURFORD, A.J. (1986): Cooling and uplift patterns in the Lepontine Alps south central Switzerland and an age of vertical movement on the Insubric fault line. Contrib. Min. Pet., 92, 413-427.

JÄGER, E. (1973): Die Alpine Orogenese im Lichte der radiometrischen Altersbestimmung. Eclogae Geol. Helv., 66/1, 11-21.

JÄGER, E., NIGGLI, E. and WENK, E. (1967): Rb-Sr-Altersbestimmung an Glimmern der Zentralalpen. Beitr. Geol. Karte Schweiz, 134, 67 p.

MCDOWELL, F.W. (1968a): Potassium-argon ages from the Ceneri Zone of southern Switzerland. Schweiz. mineral. petrogr. Mitt., 48/1, 211-212.

MCDOWELL, F.W. (1968b): Potassium-argon ages from the Valle d'Ossola section of the Ivrea-Verbano Zone (northern Italy). Schweiz. mineral. petrogr. Mitt., 48/1, 205-210.

MOTICSKA, P. (1970): Petrographie und Strukturanalyse des westlichen Bergeller Massivs und seines Rahmens. Ph. D. dissertation, University of Basel, 443 p.

RÖGL, F., CITA, M.B., MÜLLER, C. and HOCHULI, P. (1975): Geochronology of conglomerate bearing molasse sediments near Como (Italy). Riv. It. Pal. Strat., 81/1, 57-88.

SCHMID, S.M., ZINGG, A. and HANDY, M. (1986): The kinematics of movements along the Insubric Line and the emplacement of the Ivrea Zone. Tectonophysics, in press.

STEIGER, R.H. and JÄGER, E. (1977): Subcommission on Geochronology: Convention on the use of decay constants in geo- and cosmochronology. Earth Plan. Sci. Lett., 36, 359-362.

STEINITZ, G. and JÄGER, E. (1981): Rb-Sr and K-Ar studies on rocks from the Suretta Nappe; eastern Switzerland. Schweiz. mineral. petrogr. Mitt., 61/1, 121-133.

TROMMSDORFF, V. and NIEVERGELT, P. (1983): The Bregaglia (Bergell)-Iorio intrusions and its field relations. Mem. Soc. Geol. It., 26, 55-68.

VOGLER, W.S. and VOLL, G. (1976): Fabrics and metamorphism from tonalite, granitic augen gneiss and Tonale Series at the s. margin of the Swiss Alps, east of Bellinzona. Schweiz. mineral. petrogr. Mitt., 56, 635-640.

VOGLER, W.S. and VOLL, G. (1981): Deformation and metamorphism at the south-margin of the Alps, east of Bellinzona, Switzerland. Geol. Rundschau, 70, 1231-1262.

WAGNER, G.A., REIMER, G.M. and JÄGER, E. (1977): Cooling ages derived by apatite fission-track, mica Rb-Sr and K-Ar dating: the uplift and cooling of the Central Alps. Mem. Ist. Geol. Min. Univ. Padova, 30, 27 p.

WENK, E. (1970): Zur Regionalmetamorphose und Ultrametamorphose im Lepontin. Fortschr. Miner., 47, 34-51.

WENK, H.R. (1973): The structure of the Bergell Alps. Eclogae Geol. Helv., 66/2, 255-291.

Manuscript received December 12, 1985; revised manuscript accepted June 9, 1986.