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Autor(en): **Zingg, André / Hunziker, Johannes C.**

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The age of movements along the Insubric Line West of Locarno (northern Italy and southern Switzerland)

By André Zingg[1]) and Johannes C. Hunziker[2])

Keywords: Insubric Line, Canavese, K-Ar ages, low-grade Alpine metamorphism.

ABSTRACT

Permo-Mesozoic Canavese sediments are pinched in between the pre-Alpine high-grade metamorphic Ivrea Zone and the Alpine metamorphosed Sesia Zone along the Insubric Line W of Locarno. According to the "illite crystallinity" these sediments were deformed under anchi- and epizonal conditions. Synkinematically formed white mica in the mylonitized Canavese sediments yields the following K-Ar age ranges: 60–76 Ma at the southwestern end, 28–43 Ma in the central part and 19–26 Ma in the northeastern part of the Insubric Line W of Locarno. The youngest age group dates the main uplift and dextral strike-slip movements of the Insubric Line, comprising mylonites in the NE and cataclasites in the SW. This activity correlates with Late Oligocene to Early Miocene rapid cooling and uplift of the Central Alps.

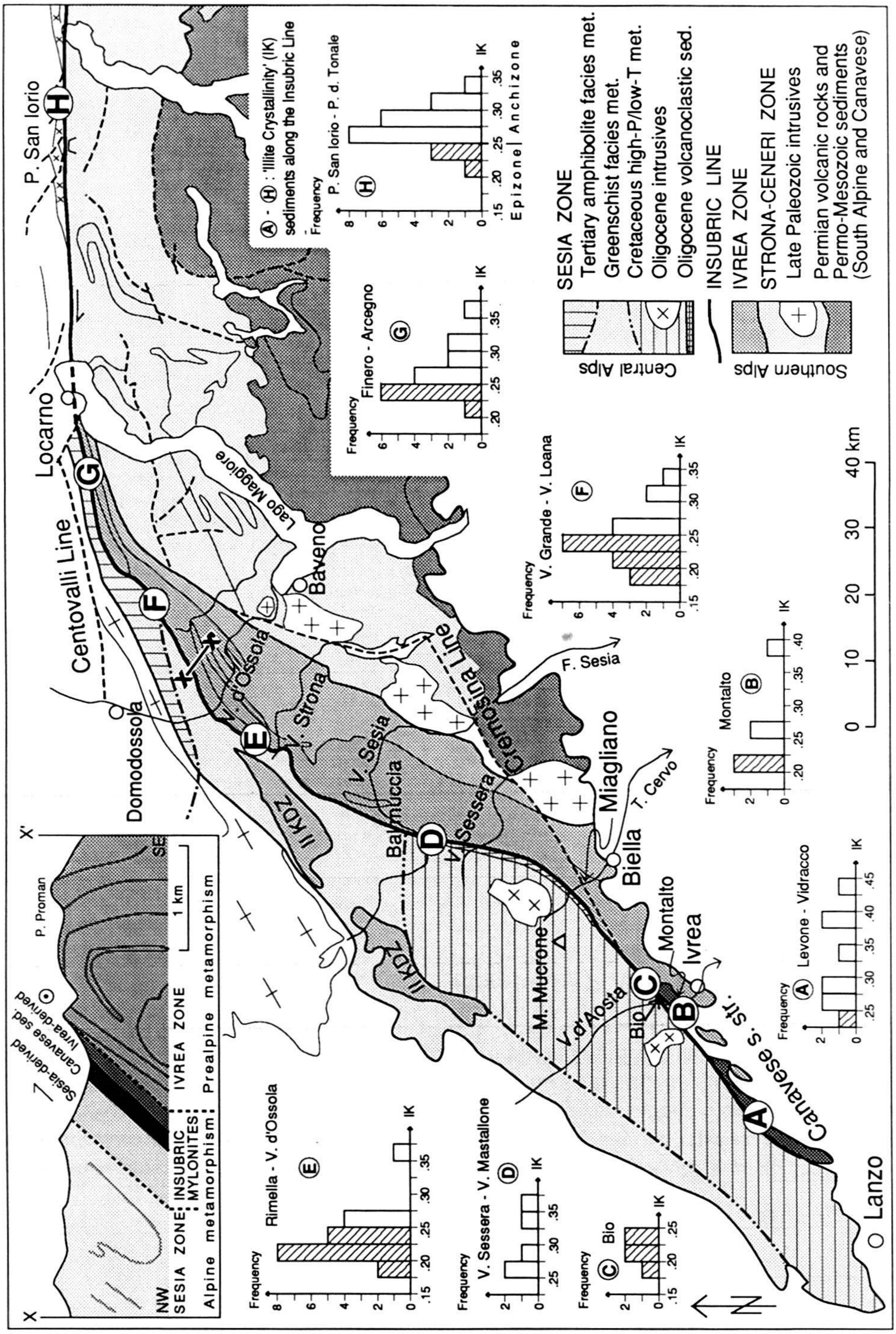
ZUSAMMENFASSUNG

Westlich von Locarno sind permo-mesozoische Canavese Sedimente zwischen der präalpin hochmetamorphen Ivrea Zone und der alpin metamorphen Sesia Zone entlang der Insubrischen Linie eingeschuppt. Gemäss der «Illitkristallinität» wurden die Canavese Sedimente unter den Bedingungen der Anchi- und Epizone verformt. Synkinematisch gebildete Hellglimmer aus mylonitisierten Canavese Sedimenten ergeben folgende K-Ar Altersgruppen: 60–76 Ma im südwestlichen Teil, 28–43 Ma im zentralen Teil und 19–26 Ma im nordöstlichen Teil der Insubrischen Linie. Die Alterswerte zwischen 19 und 26 Ma datieren grosse Vertikal- und Horizontalbewegungen, welche im NE Mylonite und im SW Kataklasite generiert haben. Diese Bewegungen können mit der schnellen Abkühlung und Hebung der Zentralalpen im späten Oligozän und frühen Miozän korreliert werden.

1. Regional setting and aim of the investigation

The Insubric Line separates the Central Alps (Cretaceous and Tertiary metamorphism) from the South Alpine basement (pre-Alpine consolidation). In addition to vertical displacements documented by contrasting metamorphic histories on either side of the Insubric Line, large-scale dextral strike-slip movements are deduced from paleogeographic reconstructions (Laubscher e.g. 1971a, b, 1988) as well as from structural evidences like the dragged tonalite tail of the Oligocene Bregaglia intrusion (Fumasoli 1974).

[1]) Geologisch-Paläontologisches Institut, Bernoullistrasse 32, CH–4056 Basel.
[2]) Institut de Minéralogie et Pétrographie, BFSH 2, CH–1015 Lausanne.



Ⓐ - Ⓗ : 'Illite Crystallinity' (IK) sediments along the Insubric Line
P. San Iorio - P. d. Tonale
Finero - Arcegno
V. Grande - V. Loana
Montalto
Levone - Vidracco
Rimella - V. d'Ossola
V. Sessera - V. Mastallone
Bio
Frequency
IK
E p i z o n e | A n c h i z o n e
SESIA ZONE
Tertiary amphibolite facies met.
Greenschist facies met.
Cretaceous high-P/low-T met.
Oligocene intrusives
Oligocene volcanoclastic sed.
INSUBRIC LINE
IVREA ZONE
STRONA-CENERI ZONE
Late Paleozoic intrusives
Permian volcanic rocks and Permo-Mesozoic sediments (South Alpine and Canavese)
Central Alps
Southern Alps
0 10 20 30 40 km
P. San Iorio
Locarno
Centovalli Line
Lago Maggiore
Baveno
Domodossola
V. d'Ossola
V. Strona
V. Sesia
Cremosina Line
F. Sesia
Miagliano
T. Cervo
Biella
Balmuccia
V. Sessera
II KDZ
M. Mucrone
Montalto
Ivrea
V. d'Aosta
Bio
Canavese s. str.
Lanzo
X
X'
NW
SESIA ZONE
INSUBRIC MYLONITES
IVREA ZONE
SE
Alpine metamorphism
Prealpine metamorphism
Sesia-derived
Canavese sed.
Ivrea-derived
P. Proman
1 km
N

This study considers the westernmost segment of the Insubric Line between Locarno and Lanzo (Fig. 1), i.e. the Canavese Line. The goal of the present investigations was to better constrain the age of displacements along the Insubric Line. Basically, the age of movement zones can be determined in three different ways:

(1) Age-bracketing with stratigraphic or magmatic events. Precise dating is possible if sedimentation or magmatism is syntectonic. The Oligocene magmatism is such a time marker in parts of the Sesia Zone.

(2) For fault zones with large vertical displacements, age constraints can be obtained by determining the thermal history of units on either side of the movement zone. The periods of major differential cooling correspond approximately with the age of tectonic activity (e.g. HURFORD 1986 and temperature-time diagrams in Fig. 2).

(3) Dating of synkinematically formed minerals from the matrix of mylonites within movement zones. This method of dating is restricted to a narrow range of metamorphic conditions because the results are only significant if formation ages rather than cooling or mixed ages are obtained.

The latter method was used in the present investigation. Synkinematically formed white micas from mylonitized Canavese sediments and from basement mylonites of the Insubric movement zone were dated with the K-Ar method to complement an earlier study (ZINGG et al. 1976). These data were then compared with the thermal histories derived for the adjacent Sesia and Ivrea Zones with the dating method (2) by HURFORD & HUNZIKER (1985), HURFORD (1986), KLÖTZLI (1988) and HURFORD et al. (in press).

2. Insubric Line West of Locarno

2.1 Geological units

Three geological units are involved in Insubric tectonics W of Locarno (SCHMID et al. 1987): (1) the Sesia Zone, (2) the Canavese sediments and (3) the Ivrea Zone.

(1) The Sesia Zone underwent Tertiary amphibolite facies metamorphism in the Locarno region, greenschist facies metamorphism in the central part and Cretaceous high-pressure/low-temperature metamorphism in the westernmost part (Fig. 1 and see e.g. REINHARDT 1966; NIGGLI & ZWART 1973; COMPAGNONI et al. 1977; FREY et al. 1980). This metamorphic zonation reflects different tectonometamorphic histories along strike of the Sesia Zone, as evidenced by the radiometrically derived temperature-time plots in Fig. 2.

(2) The Permo-Mesozoic Canavese sediments along the Insubric Line (e.g. NOVARESE 1929; BAGGIO 1965; AHRENDT 1972) show a strong stratigraphic affinity to the South Alpine sediments. They occur (a) as small discontinuous imbricates along the mylonitized margins of the Sesia and Ivrea Zones (Canavese sensu lato; see inset Fig. 1) and (b) in graben-like structures in the southwestern part of the area (Canavese sensu stricto). The latter occurrence is situated in the southwestern continuation of the

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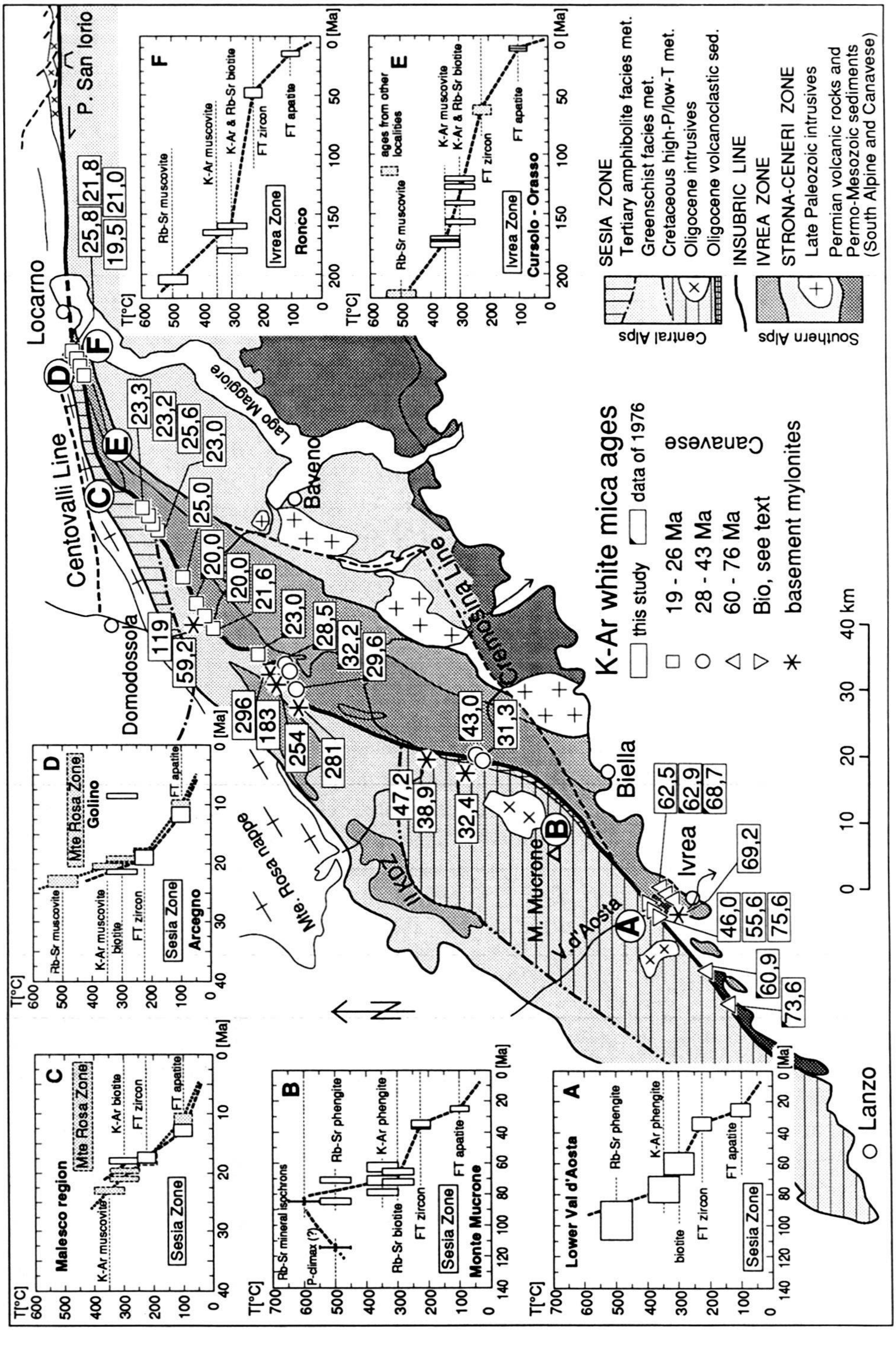
Fig. 1. Map of the Insubric Line and the adjacent units west of Locarno showing the regional distribution of "illite crystallinity" in the Canavese sediments. The crystallinity measured in the Canavese sensu lato samples is slightly better than in the sediments pinched along the Iorio-Tonale segment of the Insubric Line E of Locarno. Inset: schematic section across the Insubric mylonite belt in the Val d'Ossola.


K-Ar white mica ages
this study
data of 1976
19 - 26 Ma
28 - 43 Ma
60 - 76 Ma
Bio, see text
basement mylonites
Canavese
SESIA ZONE
Tertiary amphibolite facies met.
Greenschist facies met.
Cretaceous high-P/low-T met.
Oligocene intrusives
Oligocene volcanoclastic sed.
INSUBRIC LINE
IVREA ZONE
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Late Paleozoic intrusives
Permian volcanic rocks and Permo-Mesozoic sediments (South Alpine and Canavese)
Central Alps
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Locarno
Centovalli Line
P. San Iorio
Domodossola
Baveno
Lago Maggiore
Cremosina Line
Biella
Ivrea
Lanzo
M. Mucrone
V. d'Aosta
Mte. Rosa nappe
II DK
40 km
Lower Val d'Aosta
Monte Mucrone
Malesco region
Arcegno
Golino
Ronco
Cursolo - Orasso
Sesia Zone
Ivrea Zone
Mte Rosa Zone
Rb-Sr muscovite
K-Ar muscovite
K-Ar biotite
K-Ar & Rb-Sr biotite
Rb-Sr phengite
K-Ar phengite
Rb-Sr biotite
Rb-Sr mineral isochrons
P-climax (?)
FT zircon
FT apatite
ages from other localities
T[°C]
[Ma]

South Alpine sediments which are locally preserved S of the Cremosina Line (Fig. 1). However, in contrast to the South Alpine sediments the Canavese sediments are strongly tectonized and show a low-grade Alpine metamorphism.

(3) The Ivrea Zone comprises pre-Alpine amphibolite to granulite facies rocks of the South Alpine lower and intermediate crust (e.g. SCHMID 1967; ZINGG et al. 1990). The thermal history derived from radiometric age determinations (diagrams E and F in Fig. 2) suggests that the Ivrea Zone cooled to below ca. 300 °C during Early Mesozoic time. Alpine ductile deformation of the Ivrea Zone is restricted to its mylonitized northwesternmost rim along the Insubric Line. Faults and thrusts presumably of Alpine age occur within the Ivrea Zone and other parts of the South Alpine basement (SCHUMACHER 1990). Large-scale flexural slip folding (Proman antiform, inset Fig. 1) is related to steepening of the Ivrea crustal section (ZINGG et al. 1990).

2.2 Segments of the Insubric Line

The age and conditions of deformation change along strike of the Insubric Line W of Locarno. Three segments can be distinguished (Fig. 1):

(1) The northeastern segment, approximately between Locarno and the Val Sesia,

(2) The central segment, approximately between the Val Sesia and the Val Sessera,

(3) The southwestern segment, approximately between the Val Sessera and Lanzo.

Segment (1) is dominated by ductile deformation, segments (2) and (3) by brittle faulting overprinting older mylonites. These segments coincide with regions of different age and metamorphic facies in the adjacent Sesia Zone (Figs. 1 and 2). The structural relationship among deformations along the Insubric Line and within the adjacent units of the Central Alps are treated in the papers of KRUHL & VOLL (1976); STECK (1984, 1990); HEITZMANN (1987); SCHMID et al. (1987, 1989); MERLE et al. (1989).

The northeastern segment

The Insubric Line between Locarno and the Val Sesia is characterized by a greenschist facies mylonite belt of about 1 km width and only subordinate brittle deformation. This mylonite belt is known variously in the literature as "Scisti di (Fobello e) Rimella" (e.g. SACCHI 1977) or "Südliche Phyllonit-Zone" (REINHARDT 1966) and comprises mylonitized Sesia basement, Permo-Mesozoic Canavese sediments and Ivrea basement (SCHMID et al. 1987). Most of the lineations of the Sesia-derived mylonites plunge down-dip and their sense of shear indicate uplift and backthrust of the Sesia Zone with respect to the Ivrea Zone. In the Ivrea-derived mylonites the lineations are generally horizontal or gently E- to NE-dipping and show a dextral sense of shear

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Fig. 2. Sketch map with the K-Ar white mica ages from the basement mylonites and mylonitized Canavese sediments, including the recalculated data of ZINGG et al. (1976). Insets: radiometrically derived thermal history of the Ivrea and Sesia Zones according to: A: HUNZIKER (1974, unpublished), STÖCKHERT et al. (1986), HURFORD et al. (in press); B: HURFORD & HUNZIKER (1985), OBERHÄNSLI et al. (1985); C and E: KLÖTZLI (1988), BÜRGI & KLÖTZLI (1990); D and F: HURFORD (1986).

(Schmid et al. 1987). The lithological and structural boundaries do not always coincide. The Canavese sediments are located either at the lithological boundary between Sesia- and Ivrea-derived mylonites (see inset Fig. 1) or occur within the Ivrea-derived mylonites. Most but not all the Canavese sediments exhibit horizontal to gently dipping lineations.

Variably sheared and metamorphosed mafic and granitic dykes are found in the Sesia Zone between the Val d'Ossola and Locarno (Reinhardt 1966). They cross-cut the foliation and structures presumably formed during the climax of the Tertiary regional metamorphism in the central part of the Sesia Zone. Along the Insubric Line, however, these dykes are mylonitized and show down-dip lineations indicative for the uplift of the Sesia Zone. Thus these dyke intrusions were pre- to synmylonitic. A biotite K-Ar age of 30 Ma was obtained by Klötzli (1988) from a relatively undeformed dyke (age of intrusion?) whereas mylonitized dykes yield K-Ar biotite ages of 25 and 18 Ma in the Finero-Malesco region (Klötzli 1988) and 21 Ma near Locarno (Hurford 1986).

The central segment

Towards the SW, the Ivrea-derived part of the Insubric mylonite belt with the horizontal to moderately inclined lineations narrows progressively until it is no longer found SW of the Val Strona. Also the Sesia-derived mylonites which accommodated uplift are only moderately developed and merge with a zone of cataclastic deformation in the Val Sessera region (Schmid et al. 1989). This southwestward ductile to brittle transition is consistent with the very low grade to absent Tertiary metamorphic overprint of the Cretaceous high-pressure/low-temperature assemblages in the adjacent Sesia Zone (Fig. 1). Thus, Tertiary differential uplift is modest along this segment of the Insubric Line. This is also evidenced by the fact that Oligocene igneous rocks are exposed at about the same topographic level in the Sesia Zone (Biella intrusion, volcanoclastic cover) as in the Ivrea Zone (tonalite of Miagliano, Carraro & Ferrara 1968; Dal Piaz et al. 1979).

In addition to the post-Oligocene cataclastic deformational zone mentioned above, an older greenschist facies mylonite zone affects the rim of the Ivrea Zone (mylonite belt 1 of Schmid et al. 1989). It predates the Oligocene volcanoclastic cover and shows moderately N-dipping lineations with a dextral sense of shear. According to Schmid et al. (1989), these mylonites may have formed during pinching of the Canavese sediments between the Ivrea and Sesia basement units and were not generated during subduction or exhumation of the Sesia high-pressure/low-temperature rocks (absence of high-pressure assemblages and opposite sense of shear).

The southwestern segment

This segment is characterized by several, variably aged faults which have not yet been integrated into a consistent kinematic framework. The Sesia Zone shows Cretaceous high-pressure/low-temperature assemblages both in country rocks and in shear zones (e.g. Hunziker 1974; Compagnoni et al. 1977; Stöckhert et al. 1986). Canavese sediments N of the town of Ivrea are found in two different tectonic positions

(AHRENDT 1972; BIINO & COMPAGNONI 1989): near the locality of Bio, a sequence of pelites and siliceous limestones are pinched between the Sesia Zone and felsic intrusives along a branch of the Insubric Line. These intrusives either belong to the basement of the Canavese sediments or represent a lithologically anomalous rim of the Ivrea Zone. The main mass of Canavese sediments (Canavese sensu stricto) is preserved in graben-like structures further to the S. The dismembered sequence comprises Permian volcanics and volcanoclastics, Permo-Triassic sandstones, Triassic dolomites with a brecciated top and fracture fillings, Jurassic shales, siliceous limestones and cherts and Lower Cretaceous pelagic limestones (BAGGIO 1965; ELTER et al. 1966; STURANI 1973; AHRENDT 1972). A graded quartzo-pelitic unit may represent Cretaceous flysch (D. BERNOULLI, personal communication). The similarities with the South Alpine sediments (BERNOULLI 1964; KÄLIN & TRÜMPY 1977) and basement (micaschists, phyllites and intrusives) are striking. The Canavese sensu stricto with its strong Alpine tectonization and weak metamorphism is transitional in nature between the Central and Southern Alps. Mafic rocks of the Ivrea Zone are exposed SE of the Canavese sediments.

The geology in this region is poorly understood. Not only Alpine tectonics but also the Early Mesozoic extension during Tethyan rifting may be responsible for the proximity of the Canavese sediments and lower to intermediate crustal rocks of the Ivrea Zone, as tentatively represented in Fig. 11b of HANDY & ZINGG (in press).

3. Synmylonitic metamorphism

Synkinematic mineral assemblages were investigated along strike of the Insubric Line in the Canavese sediments. In addition, a section perpendicular to the strike of the Insubric Line in the Val d'Ossola was selected to compare the synkinematic equilibration of the Canavese sediments (prograde Alpine overprint) with that of the basement mylonites (retrograde Alpine overprint with respect to their pre-Alpine metamorphic grade). The samples were studied in thin section, by X-ray diffractometry (whole-rock and mostly fractions <2 μm), and with the Guinier-de Wolff camera in order to determine the white mica polytypes in several samples. The following instrumental conditions were used to determine the "illite crystallinity": scan rate: 2° 2Θ/min, time constant: 1, receiving slits: 1°–0.2 mm–1°, chart speed: 40 mm/min, radiation: CuK_{α}. To obtain comparable results, the samples of ZINGG et al. (1976) previously measured in Bern were remeasured in Basel. The limits of the diagenetic zone/anchizone/epizone are at 4.2 and 2.5 Δ° 2Θ CuK_{α} according to KÜBLER et al. (1979).

3.1 The Canavese sediments

This sequence experienced only Alpine metamorphism and so is best suited for investigations of the degree and age of the metamorphic overprint. For this purpose the Permo-Triassic quartzo-pelitic series, the Triassic dolomites, and the siliceous limestones were selected. The assemblages summarized in Table 1 do not vary significantly along strike of the Insubric Line. They suggest synmylonitic metamorphic conditions between the anchizone and the lower greenschist facies.

Lithology and *Age*	minerals present in all samples	common minerals	sporadic minerals
Quartzo-pelitic rocks (16) *Permo-Triassic*	quartz, muscovite	albite, K-feldspar, chlorite, calcite	stilpnomelane (2), brownish sheet silicate, paragonite (1), muscovite/paragonite (3), undetermined mixed-layer (traces)
Dolomites (13) *Triassic*	dolomite, muscovite	calcite, quartz, albite, chlorite	smectite (3), chlorite/smectite (1)
Siliceous limestones (34) *mostly Jurassic ?*	calcite, quartz, muscovite	albite, K-feldspar, dolomite, chlorite	paragonite (2), muscovite/paragonite (4), smectite (1), irregular mixed-layer (4), chlorite/smectite (4), brownish sheet silicate

Table 1: Mineral assemblages of the Canavese sediments determined by X-ray diffractometry and thin section study. Number of samples in brackets.

Muscovite: Most of the K-white micas are well crystallized with "illite crystallinities" indicative of the anchizone/epizone transition (Figs. 1 and 3; For correlations between "illite crystallinity" and mineral assemblages, see Kübler et al. 1979; Frey 1986; Kisch 1987). The width of the white mica peaks varies more in the Canavese sensu stricto than in other localities and some of these peaks are characteristic for the diagenetic zone. The best crystallinities were measured in samples from Bio and from the region between the Val Sesia and Val Strona with mean "illite crystallinities" of 0.21 (5 samples) and 0.22 (9 samples), respectively. The muscovites are 2M1 polytypes. In 3 samples of the Canavese sensu stricto, an additional small amount of 1M polytype is suspected. Thus the Canavese K-white micas differ from those of the Oligocene volcanoclastic cover of the Sesia Zone which are a mixture of 2M1 and 3T polytypes and from the 3T phengitic white micas of the high-pressure/low-temperature part of the Sesia Zone (Frey et al. 1983).

Chlorite: The intensities of the basal reflections suggest a Fe-rich trioctahedral variety in all three rock types. The chlorites are well crystallized with a (002) width at half height of 0.23 ± 0.04 ($\Delta° 2\Theta$ CuK_α, 24 samples, 1s). For comparison, the mean "illite crystallinity" of the same samples is 0.26 ± 0.06 (1s).

Paragonite and muscovite/paragonite mixed-layer: Paragonite was found only in one pelitic sample NE of Balmuccia. Possibly, this sample is completely mylonitized and retrograded Ivrea basement rather than Canavese sediment. Three quartzo-pelitic samples contain muscovite/paragonite mixed-layer with 5–15% paragonite component according to the position of the (1000) reflections.

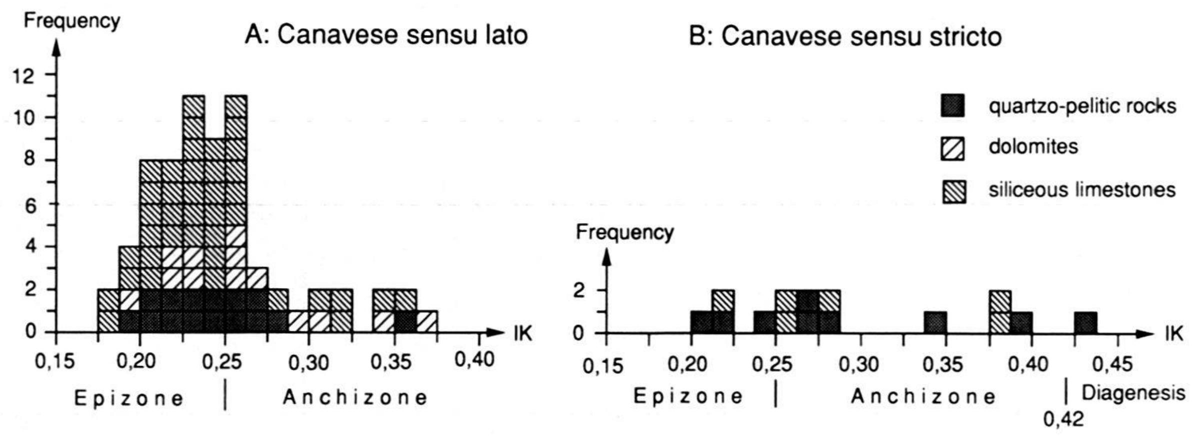

Fig. 3. "Illite crystallinity" expressed as the $\Delta° 2\Theta$ CuK_α width at half height of the (001) reflection of white mica including the remeasured data of Zingg et al. (1976). A: Canavese sensu lato, mean value of 68 samples: 0.25 ± 0.04 (1s); B: Canavese sensu stricto, mean value of 15 samples: 0.29 ± 0.08 (1s). Limits between diagenesis, anchi- and epizone after Kübler et al. (1979). For comparison, the sediments pinched along the Iorio-Tonale Line yield a mean value of 0.27 ± 0.03 (22 samples, 1s, unpublished).

Brownish sheet silicate: A minor amount of brownish sheet silicate was observed in several thin sections. Stilpnomelane was identified by X-ray in one quartzo-pelitic sample of the Canavese sensu stricto. In other samples, the presence of biotite is suspected but not proved.

Expandable sheet silicates: Smectite, regular one to one chlorite/smectite mixed-layer, and white mica randomly interstratified with a swelling component could be distinguished after treatment of the samples with glycol and heating to 550 °C for one hour. These expandable minerals were sporadically found only in the region NE of the Val d'Ossola. As the variation in "illite crystallinity" for this region lies within the same range as in other places, the growth of these expandable minerals is tentatively attributed to localized postmylonitic retrogression. Hydrothermal activity presumably related to the Centovalli fault system is documented in this region by quartz-chlorite fracture fillings postdating the Insubric mylonitization.

3.2 Basement mylonites in the Ossola section

Table 2 summarizes the mineral assemblages of the principal lithologies affected by Insubric mylonitization in the Val d'Ossola. The synkinematically formed minerals in the mylonitic matrix are indicative of lower greenschist facies conditions both in the Canavese sediments and in the basement mylonites. A slightly higher synmylonitic metamorphic grade in the region NE of the Val d'Ossola is indicated by biotites occurring both as clasts and matrix minerals in granitic and semipelitic rocks.

Within the rim of the Ivrea Zone, the mylonitic deformation overprints pre-Alpine high-grade rock and this fabric boundary between pre-Alpine and Alpine structures can be mapped. It is this fabric boundary that is traditionally referred to as the Insubric Line. On the Sesia side of the mylonite belt, there is a continuous transition of the structure and metamorphism between the Alpine metamorphosed crystalloblastic Sesia rocks and their equivalents mylonitized under greenschist facies conditions along

	Protolith	Relics and clasts	Matrix minerals / synmylonitic assemblage
SESIA-derived	Granitic rocks	K-feldspar, plagioclase or albite, ± clinozoisite, ± orthite, ± biotite	quartz, albite, muscovite, clinozoisite, sphene, ± chlorite, ± biotite?, ± actinolite
	Semipelitic rocks	K-feldspar?, plagioclase or albite, muscovite, ± biotite	quartz, albite, muscovite, epidote, sphene ± chlorite, ± biotite?, ± calcite
	Mafic rocks	plagioclase or albite, amphibole, sphene	albite, muscovite, chlorite, actinolite, sphene, clinozoisite, ± quartz, ± calcite
CANAVESE	Quartzo-pelitic rocks		quartz, muscovite, ± chlorite, ± albite, ± K-feldspar, ± calcite, ± biotite?
	Dolomites		dolomite, muscovite, ± calcite, ± quartz, ± albite, ± chlorite
	Siliceous limestones		calcite, quartz, muscovite, ± albite, ± chlorite, ± K-feldspar, ± dolomite
IVREA-derived	Paragneisses	garnet, (biotite -> chlorite + sphene), (plagioclase -> albite), ± muscovite	quartz, albite, muscovite, chlorite, clinozoisite, sphene, ± margarite, graphite?, ± brownish sheet silicate
	Mafic rocks	amphibole, plagioclase or albite, (ilmenite -> sphene)	albite, actinolite, chlorite, muscovite, sphene, clinozoisite, ± calcite, ± quartz
	Impure marbles	sphene, ± diopside, ± actinolite, ± clinozoisite, ± plagioclase or albite	calcite, quartz, ± albite, ± actinolite?, muscovite, chlorite

Table 2: Mineral assemblages of the Insubric mylonites in the Val d'Ossola determined from thin section study.

the Insubric Line. The gradational nature of the contact between these two structural units is interpreted to reflect a high lateral paleo-temperature gradient induced by the uplift and backthrusting of the hot Central Alps onto the cold South Alpine rocks during Insubric faulting (SCHMID et al. 1987).

KAW No.	Locality	Lithology	Fraction	Sheet silicates						additional phases				
							muscovite							
			[µm]	Mu	Chl	other	IK	polyt.	d(060,331) [Å]	Qtz	Ab	Cc	Kf	Opq
Canavese sensu lato:														
2551	Cortenuovo	quartzo-pelitic rock	< 2	100			0,20	2M1	1,500	x	x	x		x
2553	A. Scaredi	quartzo-pelitic rock	< 2	95	5		0,23	2M1	1,496	x	x		tr	x
2554	A. Scaredi	quartzo-pelitic rock	< 2	90	10		0,21	2M1	1,498	x	x		tr	x
2552	Loro	quartzo-pelitic rock	< 2	100			0,23	2M1	1,503	x	x			x
2555	Val Dolca	quartzo-pelitic rock	< 2	100			0,27	2M1	1,506	x	x			x
2451	Arcegno	siliceous limestone	2 - 6	±80	±10	ML:±10	0,36	n.d.	n.d.	x	x	x		
2452	Arcegno	siliceous limestone	< 2	45	55		0,25	n.d.	n.d.	x	x	x		
2455	Arcegno	siliceous limestone	2 - 6	65	35		0,23	2M1	1,499	x	x	x		
2458	Arcegno	siliceous limestone	< 2	±30	±60	ML:±10	0,28	n.d.	n.d.	x	x	x		
2544	A. Scaredi	siliceous limestone	< 2	95	5	ML: tr	0,24	2M1	1,502	x	x	x		
2543	A. Serena	siliceous limestone	2 - 6	100			0,18	2M1	1,500	x	x	x	tr	
2548	Vogogna	siliceous limestone	2 - 6	100			0,20	2M1	1,498	x	x	x		x
2459	Bio	siliceous limestone	2 - 6	55	45		0,24	2M1	1,499	x	x	x		
2460	Bio	siliceous limestone	2 - 6	30	70		0,23	n.d.	n.d.	x	x	x		
2550	Bio	siliceous limestone	6 - 20	40	60		0,21	n.d.	n.d.	x	x	x		
Canavese sensu stricto:														
2549	Montalto	siliceous limestone	< 2	75	25		0,25	2M1	1,502	x	x	x	tr	x

Table 3: Mineral assemblages of the Canavese samples used for radiometric age determination. The proportions of the sheet silicates were estimated from the peak intensities according to FREY (1978). Mu: muscovite; Chl: chlorite; ML: mixed-layer; Qtz: quartz, Ab: albite; Cc: calcite; Kf: K-feldspar; Opq: opaques; IK: "illite crystallinity"; tr: traces; n.d.: not determined.

Sample No.	Locality	Prealpine Clasts and Relics						Matrix Minerals (Synmylonitic assemblage)									
		Kf	Plg	Mu	Ep	Ap	Am	Qtz	Kf	Plg	Ep	Mu	Chl	Ap	Sph	Opq	other
Sesia-derived mylonites																	
KAW 1511	Vogogna/Val d'Ossola		x	X				X		+	x	X	x	x	x	x	Cc, Ga, Bi or Stp
KAW 1512	Bocchetta di Campello/		x	x			x	X		+	x	X	x	x		x	Cc, Bi or Stp
KAW 1513	Val Strona di Omegna		x	X	x	x		X		+	x	X	x			x	Cc
KAW 1201	Rimella/Val Mastallone	x	x	x		x		X		+	x	x		x			Stp
KAW 1099B	Scopello/Val Sesia							X		+	x	X		x	x	x	Cc
Ha 53	Val Dolca/Val Sessera	x	x	x		x		X	+	+	x	x		x		x	
Ivrea-derived mylonite																	
KAW 2450	Montalto/Val d'Aosta	Di	Act	Sph	Ep	Fsp		Cc	Qtz	Mu	Chl						

Table 4: Mineral assemblages of the basement mylonites used for radiometric age determinations. Note that most of the samples contain significant amounts of muscovite clast, i.e. white micas predating mylonitization. Sample KAW 1511 does not show a bimodal distribution of the grain-size between clasts and matrix minerals. Modes estimated in thin section: x <3 Vol%; x 3–10 Vol%; X 10–20 Vol%; **X** >20 Vol%; + Vol% not determinable. Kf: K-feldspar; Plg: plagioclase (or albite); Mu: muscovite; Ep: epidote; Ap: apatite; Am: amphibole; Qtz: quartz; Chl: chlorite; Sph: sphene; Opq: opaques; Cc: calcite; Ga: garnet; Bi: biotite; Stp: stilpnomelane.

4. Radiometric dating

23 samples of mylonitic Permo-Mesozoic Canavese sediments and mylonitized basement rocks (Tables 3 and 4) were ground, decarbonatized if necessary, and the small grain size fractions (mainly <2 μm) were separated using Atterberg cylinders (preparation outlined in HUNZIKER et al. 1986). The potassium was determined on an IL 243 flame photometer using lithium as an internal standard and argon was measured on a WG MM 1200 mass spectrometer using 99.99% 38Ar spike (SCHUMACHER 1975) calibrated against international standards GL-O and LP-6.

Tables 5 and 6 show the ages obtained from the basement samples and Canavese sediments, respectively. The ages are shown in Fig. 2 together with the data published in ZINGG et al. (1976) which were recalculated with the new constants given in STEIGER & JÄGER (1977).

5. Discussion and interpretation of the age data

5.1 Basement mylonites

The mylonitized Sesia basement rocks yield muscovite ages decreasing from 296 to 32 Ma with decreasing grain size. Most of these determinations are obviously mixed ages. The ages of the pre-Alpine muscovite clasts were only partially reset despite the strong Alpine mylonitization and retrogression of the rocks. However, the small grain size fractions of samples KAW 1099 and Ha 53 from the Val Sesia/Val Sessera area yield ages of 47, 39 and 32 Ma, i.e. ages which are close to the 43 and 31 Ma obtained from the Canavese sediments of the same region.

5.2 Canavese sediments

The following regional age pattern is observed: 19–26 Ma between Locarno and the Val Strona, 28–43 Ma between Val Strona and Val Sessera and 60–76 Ma in the Val d'Aosta region (except 2 samples from the locality of Bio). This grouping correlates

Sample No.	Locality	Lithology	Fraction [μm]	K [%]	40Ar rad . 10-6 [cm3 (STP)/g]	40Ar rad [%]	Age [Ma]
Sesia-derived mylonites							
KAW 1511	Vogogna	pegmatitic	250 - 425	8,84	42,20	92,0	119 ± 4
	(Val d'Ossola)		150 - 180	8,91	20,87	80,5	59,2 ± 2,2
KAW 1512	Bocchetta di Campello	semipelitic	250 - 425	8,77	109,7	92,58	296 ± 10
	(Val Strona di Omegna)		150 - 180	8,80	66,11	96,37	183 ± 6
KAW 1513	Bocchetta di Campello	semipelitic	250 - 425	8,38	89,20	96,04	254 ± 8
KAW 1201	Rimella (V. Mastallone)	granitic	250 - 425	8,80	104,2	97,66	281 ± 9
KAW 1099B	Scopello	semipelitic	6 - 20	5,35	9,98	76,02	47,2 ± 1,9
	(Val Sesia)		< 2	5,69	8,75	50,93	38,9 ± 2,3
Ha 53	Val Dolca/Val Sessera	granitic	< 2	5,74	7,30	57,43	32,4 ± 1,7
Ivrea-derived mylonite							
KAW 2450	Montalto/Val d'Aosta	impure marble	2 - 6	3,70	10,05	78,91	69,2 ± 0,5

Table 5: White mica K-Ar ages (± 1 s) from Sesia-derived basement mylonites.

Sample No.	Locality	Lithology	Fraction [μm]	K [%]	40Arrad . 10-6 [cm3 (STP)/g]	40Arrad [%]	Age [Ma]
Canavese sensu lato:							
KAW 2451	Arcegno/Locarno	Siliceous limestone	2 - 6	2,43	2,07	54,1	21,8 ± 0,3
KAW 2452	Arcegno/Locarno	Siliceous limestone	< 2	2,25	1,85	24,1	21,0 ± 0,4
KAW 2455	Arcegno/Locarno	Siliceous limestone	2 - 6	2,78	2,12	42,7	19,5 ± 0,3
KAW 2458	Arcegno/Locarno	Siliceous limestone	< 2	3,84	3,87	46,0	25,8 ± 0,3
KAW 2551	Cortenuovo/V. Loana	Quartzo-pelitic rock	< 2	6,28	5,73	46,87	23,3 ± 0,3
KAW 2544	A. Scaredi/Val Loana	Siliceous limestone	< 2	1,96	1,78	10,19	23,2 ± 0,6
KAW 2553	A. Scaredi/Val Loana	Quartzo-pelitic rock	< 2	7,07	7,10	43,97	25,6 ±0,3
KAW 2554	A. Scaredi/Val Loana	Quartzo-pelitic rock	< 2	5,55	5,00	83,70	23,0 ± 0,3
KAW 2543	A. Serena/Val Grande	Siliceous limestone	2 - 6	3,49	3,42	43,53	25,0 ± 0,4
KAW 2548	Vogogna/Val d'Ossola	Siliceous limestone	2 - 6	2,92	2,27	13,20	20,0 ± 0,2
KAW 2552	Loro/Val d'Ossola	Quartzo-pelitic rock	< 2	4,31	3,64	58,19	21,6 ± 0,3
KAW 2555	Val Dolca/Val Sessera	Quartzo-pelitic rock	< 2	8,28	10,16	57,06	31,3 ± 0,4
KAW 2459	Bio/Val d'Aosta	Siliceous limestone	2 - 6	4,45	8,05	81,6	46,0 ± 0,6
KAW 2460	Bio/Val d'Aosta	Siliceous limestone	2 - 6	1,75	3,84	64,2	55,6 ± 0,9
KAW 2550	Bio/Val d'Aosta	Siliceous limestone	6 - 20	2,20	6,60	74,17	75,6 ± 0,9
Canavese sensu stricto:							
KAW 2549	Montalto/Val d'Aosta	Siliceous limestone	< 2	5,96	14,74	83,29	62,5 ± 0,7

Table 6: White mica K-Ar ages (± 1 s) from the Canavese sediments.

with the distribution of metamorphic facies in the Sesia Zone and the 3 structural segments of the Insubric Line described above.

We interpret most of the ages obtained from the Canavese sediments as formation ages due to their systematic regional distribution, their independence of both rock-type and degree of deformation, and their coincidence with independently dated episodes of rapid cooling of the adjacent Sesia Zone in the NE. This interpretation is also based on experience with radiometric dating in other low-grade terrains (Hunziker 1987).

The northeastern segment (Locarno-Val Strona)

Samples KAW 2451, 2452, 2455, 2458, 2551, 2552 come from Canavese sediments located within the dextral strike-slip mylonite belt. Samples KAW 2543, 2544, 2553, 2554 and 2548 were collected at the boundary between the strike-slip and the uplift domains. All of these Canavese occurrences show horizontal to gently dipping lineations, except KAW 2543 which shows down-dipping lineations. The ages between 19–26 Ma obtained from the Canavese sediments are thus independent of the structural position of the samples and fall within a period of rapid cooling and uplift of the Sesia Zone in the Locarno-Val d'Ossola region. There, rapid cooling is evidenced by the successive closure of the muscovite Rb-Sr and K-Ar, the biotite Rb-Sr and K-Ar and the zircon fission track systems between 24 and 19 Ma years (Hurford 1986 and diagram D in Fig. 2). The K-Ar biotite ages (25, 21, 18 Ma) obtained from variably mylonitized dykes (Hurford 1986; Klötzli 1988) fall within the same time span.

Generally coeval uplift and dextral strike-slip ductile movements along this segment of the Insubric Line is also suggested by the observation that the synmylonitic metamorphic grade is about the same (greenschist facies) across the Insubric mylonites, i.e. in the Sesia-derived mylonites with predominantly down-dip lineations, in the

Canavese sediments and in the Ivrea-derived mylonites with predominantly horizontal lineations.

The central segment (Val Sesia – Val Sessera region)

The geological interpretation of the 28–43 Ma ages from the central part of the Insubric Line is difficult. This region is characterized by the transition from Tertiary greenschist facies to Cretaceous high-pressure/low-temperature metamorphism in the Sesia Zone. This implies only moderate vertical movement and a deformational regime in quartz-rich rocks at the ductile-brittle transition during the Tertiary. The temperature-time curve from the adjacent Monte Mucrone area in the Sesia Zone (Diagram B in Fig. 2 and HURFORD & HUNZIKER 1985) suggests an episode of accelerated cooling around 30 Ma (zircon and apatite fission track data). Alternatively, the ages from the Canavese sediments may be related to the older mylonitization that predate the Oligocene magmatism (mylonite belt 1 of SCHMID et al. 1989).

The southwestern segment (Val Sessera – Lanzo)

In the lower Val d'Aosta region, Cretaceous ages were obtained in all tectonic units:

(1) Both annealed and mylonitic high-pressure/low-temperature rocks of the Sesia Zone yield K-Ar white mica ages between 69 and 86 Ma (HUNZIKER 1974; STÖCKHERT et al. 1986). Radiometrically derived temperature-time curves evidence a major Late Cretaceous cooling episode in this part of the Sesia Zone (HURFORD et al., in press; diagram A in Fig. 2). The Cretaceous ages and deformations are related to different stages of the subduction and exhumation of the Sesia Zone (e.g. OBERHÄNSLI et al. 1985).

(2) Ages of 46, 56 and 76 Ma were obtained at the locality of Bio, where Canavese sediments are pinched between Sesia and South Alpine basement. The two younger ages are interpreted as mixed ages, presumably due to subsequent deformations concentrated along this branch of the Insubric Line system.

(3) The sediments of the Canavese sensu stricto show an anchi- to epizonal metamorphism and yield mica ages between 60 and 74 Ma.

(4) Sample KAW 2450 represents a mylonitized impure marble from the rim of the Ivrea Zone. Relics and clasts of diopside, actinolite, epidote and sphene document the pre-Alpine high-grade evolution of this rock sequence. The fine grained newly formed white mica in the mylonitic matrix gives an age of 69 Ma.

These ages suggest that in the lower Val d'Aosta region not only the Sesia Zone but also the Canavese sediments and part of the Ivrea Zone were affected by a Cretaceous tectonometamorphic event. However, the two latter units are separated from the high-pressure/low-temperature Sesia Zone by Tertiary faults belonging to the Insubric Line system. Thus the three units were at different positions during Cretaceous tectonics, and the present-day configuration with Cretaceous high-pressure/low-temperature rocks adjacent to greenschist facies and lower grade rocks was established during Tertiary tectonics. The relative position of the three units during the Cretaceous can not yet be reconstructed as neither the Tertiary displacements along the Insubric and Cremosina Lines nor the internal deformation of the involved units are yet quantified.

In addition, these structural elements have yet to be placed in the framework of the Tertiary deformations recently recognized in other regions of the Southern Alps (PIERI & GROPPI 1981; HUNZIKER & MARTINOTTI 1984; BERNOULLI et al. 1990; LAUBSCHER 1990; ROURE et al. 1990; SCHUMACHER 1990).

6. Summary and conclusions

The Insubric fault belt W of Locarno is a composite structure in which Canavese sediments and basement rocks are involved. Late Oligocene to Early Miocene movements generated a 1 km wide mylonite belt in the NE which merge into a cataclastic zone in the SW. There, these cataclasites overprint older mylonites that pre-date Oligocene magmatism.

The K-Ar ages of the Canavese sediments range between 19–26 Ma in the northeastern part, 28–43 Ma in the central part and 60–76 Ma in the southwestern part of the Insubric Line. The Cretaceous ages document Eo-Alpine tectonometamorphic events not only in the Sesia Zone but also in the Canavese sediments and along the rim of the Ivrea Zone in the lower Val d'Aosta region. However, the tectonic setting of the Cretaceous event is not yet known because the relative position of these three units was significantly modified by Tertiary activity of the Insubric Line and related faults.

The 19–26 Ma ages were obtained mainly in Insubric mylonites that accommodated dextral strike-slip. These ages coincide with the Late Oligocene and Early Miocene uplift and rapid cooling of the Central Alps, previously documented by HURFORD (1986). Thus uplift and dextral strike-slip movements are broadly synchronous. Further, mylonitization along this segment of the Insubric Line is contemporaneous with major deformation in the Helvetic domain (SCHMID et al. 1989). According to the cooling curves of HURFORD (1986), the ductile/brittle boundary for quartz-rich rocks was reached prior to Middle Miocene time in the Locarno region. Differential vertical movements became then minor as documented by the apatite fission-track ages of 15 and 12 Ma in the Ivrea and Sesia Zones, respectively (see also diagrams D and F in Fig. 2). Thus the activity of the Insubric movement zone W of Locarno was strongly reduced during the Middle to Late Miocene deformations recognized in the Po plain, Simplon region and Jura mountains.

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