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RB-SR AND K-AR AGE DETERMINATION AND THE ALPINE TECTONIC HISTORY OF THE WESTERN ALPS

(with 19 figures, 5 tables and 2 plates)

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I. INTRODUCTION

The aim of this work was to date the different events of the polyphase history of Alpine metamorphism and tectonics in the Western Alps by means of Rb-Sr and K-Ar age determinations on minerals and rocks. For this purpose more than 100 new K-Ar and Rb-Sr analyses on 65 different samples are presented and the resulting consequences for the geologic picture are discussed.

In this paper special emphasis is laid on the Alpine history. The pre-Alpine events are mentioned only where new evidence has been found.

In contrast to the Eastern and Central Alps where several hundreds of age data have long been available, the Western Alps, from the geochronological point of view, are less well known (until 1970 not more than 20 K-Ar and Rb-Sr data were known from the Western Alps).

II. GEOLOGICAL SETTING

In contrast to the Eastern and Central Alps where several hundreds of age metamorphism has been clear for some time, the formation of the Western Alps is generally thought to be monophase.

In the Eastern Alps Kober (1955), Tollmann (1963 and 1966), Oberhauser (1964 and 1968), Clar (1965), Woletz (1967) and Mueller (1973) postulated an early Alpine phase of Alpine tectonics in the Cretaceous, based mainly on stratigraphical and sedimentological criteria.

This early phase has been dated geochronologically mainly in the surroundings of the Tauern-window by Oxburgh et al. (1966), Schmidt et al. (1967), Miller et al. (1967), Harre et al. 1968), Cliff et al. (1971) and Brewer (1969). All came to the conclusion that an early phase of tectonics and metamorphism occurred in the interval between 65 and 90 m.y.

A second phase was dated between 40 and 10 m.y. by the same authors. The later phase was found to have occurred between 35 and 40 m.y. in the Central Alps (Jäger (1970), Hunziker (1970)). The possibility of an earlier phase in the Central and Western Alps is still a matter for discussion.

Trümpy (1960 and 1973) supposes that the East Alpine palaeo- or eo-Alpine phase pinches out towards the West but he admits that a possible Western extension cannot be excluded.

ARGAND (1916) postulated a late Mesozoic phase of early Alpine movements and STAUB mentioned Cretaceous folding in the Valais belt. On the other hand according to DEBELMAS and LEMOINE (1970) and LAUBSCHER (1970) the beginning of overthrusting in the Central and Western Alps is set into the Eocene. This movement is dated by overthrust of lower Oligocene on to Eocene rocks. As the first metamorphic ophiolite pebbles are found in the lower Oligocene conglomerates of the Molasse basin (FUECHTBAUER (1964) and DE GRACIANSKY et al. (1971)) only a few million years are available to account for folding, metamorphism, erosion, and redeposition of the metamorphosed rocks.

A crucial point overlooked in this model is the low heat conductivity of rocks and the difficulty of bringing into the rock system the necessary thermal energy acquired for a metamorphism in a rather short period of time. In addition, radiometric data presented here indicate the existence of an early Alpine event in the Western Alps.

In the following we shall concentrate on the Western Alps, which are built up of three main units: the Helvetic, Pennine and Austroalpine (see Fig. 1).

The Helvetic zone consists of the Hercynian and older massifs: the Aare-Gotthard, Mont-Blanc - Aiguilles Rouges, Belledonne, Pelvoux and Mercantour massifs, and the Subalpine Helvetic units, both of which are only slightly affected by Alpine metamorphism. The Helvetic units are thrust over sediments of the Molasse basin in the Swiss Alps. The period of overthrusting must be younger than Eocene according to TRÜMPY (1969) since Lower Oligocene sediments have been overridden. FREY et al. (1973) and FREY et al. (in preparation) have been able to show in the Central Alps that an early Oligocene metamorphic event occurred while these nappes were already close to their present position and clearly not anymore in their depositional environment. A later tectonic event during Miocene time was also detected there.

In the Pennine zone we distinguish between the pre-Triassic basement or core of the nappes: Ticino nappes, Monte-Rosa-Bernhard, Gran Paradiso, and Dora Maira and the fossiliferous Mesozoic Schistes lustrés or Bündner Schiefer cover. In the French Alps the Pennine zone is divided into the external Briançonnais and the internal Piemont domaines. The Briançonnais is overriden by sediments of, according to ELTER et al. (1966), presumably Cretaceous to Eocene age - the Helminthoid Flysch, so that this movement must have taken place not before Upper Eocene time.

The age of the oldest Briançonnais overthrust by the Piemont domain is unknown, but must be at least Upper Cretaceous as will be seen later.

The time of metamorphism of the Central Pennine, the socalled Lepontine region was dated by JÄGER (1970) and HUNZIKER (1970) at 36 and 38 ± 2 m.y. respectively. As the total rock systems of the Lepontine gneisses remained closed for Rb and Sr during the Alpine metamorphism (JÄGER, 1970), and the calcite in the intercalated metamorphosed Mesozoic Bündner Schiefer have sedimentary $0^{18}/0^{16}$ isotopic ratios (BAERTSCHI, 1957), the heat transport by a fluid phase is assumed to be of minor extent. Without heat transport by a fluid phase it takes considerable time (due to the low heat conductivity in rocks) to bring into a rock system the

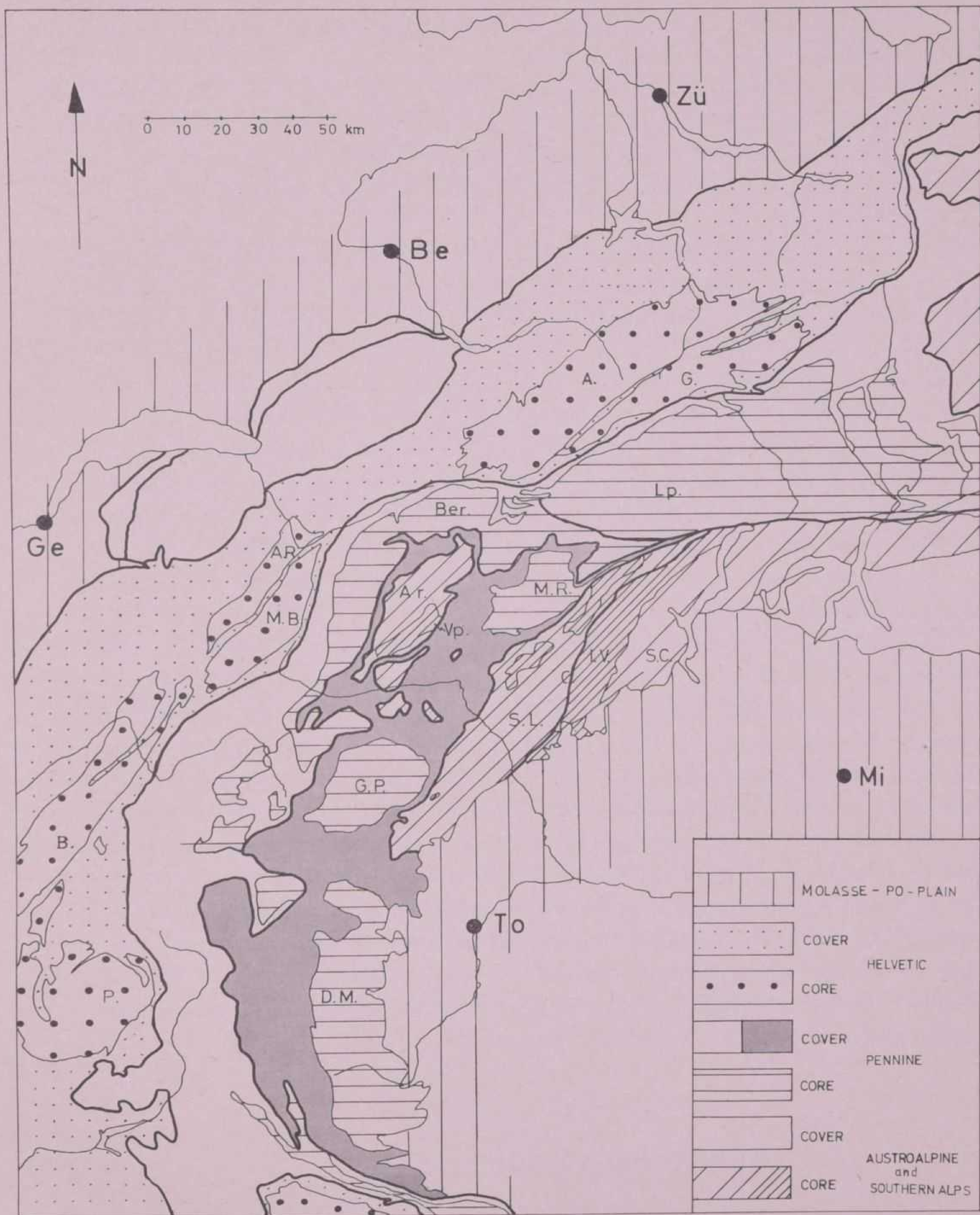

FIG. 1 - Tectonic sketch map of the central and western Alps. Fixpoints: Mi = Milano, To = Torino, Ge = Genève, Be = Bern, Zü = Zürich. Tectonic units: Molasse and Po-plain. Helvetic domain, A = Aaremassiv, G = Gotthardmassiv, A-R = Aiguilles-Rouges, M-B = Montblanc, B = Belledonne, P = Pelvoux. Pennine Domain, core, Lp = Lepontine area, MR = Monte Rosa, Ber = Bernhard, GP = Gran Paradiso, DM = Dora Maira, cover, shaded area = Piemont basin, white = Briançonnais and Valais through. Austroalpine and Southern Alps, Dent Blanche nappe system with Ar = Arolla- and Vp = Valpelline-nappe, S.L. = Sesia-Lanzo zone, C = Canavese, IV = Ivrea-Verbano zone, SC = Strona-Ceneri zone.

necessary heat for metamorphism (OXBURGH and TURCOTTE (1970 and 1971)). OXBURGH and TURCOTTE (1970) estimated this time difference to be as big as 30 m.y. On this basis it can be concluded that an earlier phase of tectonics must account for the Lepontine phase of metamorphism.

We will see later in how far this concclusion is valid also for the Western Alps. In the Western and Central Alps VAN DER PLAS (1959), NIGGLI (1960) and BEARTH (1959 + 1962) proposed an earlier phase of metamorphism on petrographic evidence. This earlier phase has been dated in the eclogites by K-Ar analysis on alkali-amphiboles at 80-100 m.y.

The Austroalpine of the Western Alps is only developed to a minor extent but is very important in consideration of the tectonic history. There is the Dent Blanche nappe, and the Sesia- Canavese and Ivrea-zones, which represent the root of this Austroalpine nappe (CARRARO *et al.* 1970). The Ivrea-zone is characterized by several geophysical discontinuities. NIGGLI (1946) discussed a gravity anomaly associated with the Ivrea-zone. The symposium Ivrea-Verbano in 1968 contributed a large amount of additional data, supporting the interpretation that under the Ivrea-zone the Moho-discontinuity nearly reaches the surface as a wedge of upper mantle material. The Ivrea-zone is interpreted as the outcrop of a transition zone between the upper mantle and the lower crust. (BERKHEMER (1968), GIESE et al. (1970)).

Trace lead analysis by GRAESER and HUNZIKER (1968) provide strong evidence in favour of this interpretation.

According to A. BIANCHI and Gb. DAL PIAZ (1963) the Sesia-zone consists of pre-Permian basement. The Canavese-zone is built up partly of phyllonites of Ivrea- and Sesia-zone rocks and partly of sediments presumed to be of Upper-Permian to Lower Cretaceous age and of Permian granites and porphyries (AHRENDT 1972). The Dent-Blanche nappe consists of two parts: the Arolla series corresponding to the Sesia-zone and the Valpelline series equivalent to the Ivrea-zone.

No geologic evidence indicating the time of movement and metamorphism of the Dent Blanche nappe is known. Phengite Rb-Sr and K-Ar ages show clearly, however, that an Upper Cretaceous high pressure-low temperature metamorphism affected these structural elements. The age of the movement appears to increase from Miocene to Upper Cretaceous, going from the Helvetic to the Austroalpine parts of the chain. This time interval would be sufficient to allow for the slow evolution of heat in the nappes.

III. GEOCHRONOLOGICAL RESULTS

1) Analytical Methods

Argon Measurements: Argon was analyzed on a Varian Mat GD 150 Mass spectrometer and on a glass line described by PURDY (1972) and calibrated according to TSCHEDJEMOV, TODT and LIPPOLT (1971).

The spike used was from Clusius, Zürich 99,98 % Ar^{38}. The spike was calibrated against Bern muscovite 4 m using a value of $6{,}31 \times 10^{-6}$ cm^3 Ar^{40} rad. / g STP.

This spike yielded values of: 27,86 ± 0,33 x 10^{-6} cm^3 Ar^{40} rad./g STP for USGS P207 Mu. 6 measurements and of 5,16 x 10^{-6} cm^3 Ar^{40} rad./g STP for Bern Biotite 4B. The accuracy of the argon measurements determined on repeated argon analyses of the same sample is ± 1,2 %. The measured 40/36 ratios for atmospheric argon range between 285,5 and 298,5 depending on the filament, ion repeller voltage and trap current. Over a period of 6 months with the same setting the value is stable to within ± 0,6 %. For our measurements the value of 298,5 ± 1,5 was found. The background of the line is in the order of magnitude 1 - 5 10^{-8} cm^3 Ar^{40} STP for the whole extraction process a maximum of 0,5 x 10^{-8} cm^3 Ar^{40} rad. STP was found. The line was usualy baked over night for 9 hours at 150°C. This procedure gives a starting vacuum around 5 x 10^{-8} Torr.

Potassium Measurements: For potassium contents above 2 % the standard flame photometric techniques described extensively by Purdy and Jäger (1973) where used. The attained accuracy was ± 1 % on duplicate analyses. For potassium contents below 2 %, particularly for alkali-amphiboles ranging between 100 and 5000 ppm K, potassium was determined by isotope dilution technics using a K^{40} spike.

The measurements were made on a VARIAN MAT CH 4 solid source mass spectrometer on a tantalum single filament source. The Bern muscovite 4 M gave a value of 8,77 % K. The reproducibility of the method was tested on repeated analyses of one basalt sample giving a value of 0,5561 ± 0,0012 % K.

The blank for the overall procedure (chemistry and mass spectrometry) is in the order of magnitude of 0,5 μg K which represents for the analyzed sample weights about ± 1 ppm of K.

For the age calculation the following constants were used.

$$\lambda_\varepsilon = 0{,}585 \times 10^{-10}\ y^{-1}$$
$$\lambda_\beta = 4{,}72 \times 10^{-10}\ y^{-1}.$$

For the atomic abundance of K^{40} the value of 1,19 x 10^{-4} moles K^{40}/mole K was used.

The 2σ error on the age determination was estimated to be ± 4 %.

The errors being ± 1 % on the K content
± 1 % on the spike concentration
± 0,6 % on the air argon ratio,

and a possible drift of around 1 % against international mean values of standards.

Rb-Sr Measurements: For the Rb-Sr measurements the following physical constants were used:

Sr^{88}/Sr^{86} common	=	8,432	(atoms)
Sr^{86}/Sr^{84} »	=	17,49	»
Sr^{87}/Sr^{86} »	=	0,7091	»
Rb^{85}/Rb^{87} »	=	2,591	»
decay constant	=	$1{,}47 \cdot 10^{-11}$ yr^{-1}.	

2) Compilation of the Data

The analytical data are listed in Tables 1, 1a, 2, 2a and 3. Descriptions of the samples and localities are given in appendix 1. The age data are also presented in Plate I, regional distribution of the Rb-Sr and K-Ar ages of biotites, Plate II, regional distribution of K-Ar ages on white micas, and Fig. 2, tectonic sketch map of the Central and Western Alps (as Fig. 1) with the distribution of the analyzed amphiboles.

3) Discussion of the Age Results

a) *Rb-Sr*

Rb-Sr ages on micas of the Alps have long been interpreted as giving the cooling time after a metamorphism. Jäger, 1962, Jäger, Niggli, Wenk (1967). From the coincidence of the field of Alpine staurolite with the field of young muscovites in the Lepontine area, Jäger deduced a temperature of about 500°C for the Alpine closing of the Rb-Sr system of muscovites under regional metamorphic conditions. For the closure of the biotite Rb-Sr system under analogous conditions E. Jäger gives a temperature of 300°C which is in good agreement with calculations of Dodson (1973).

Table 1 - Rb-Sr Data and Age Results on Minerals and Rocks of the Ivrea-Zone and Strona-Ceneri-Zone

KAW	Rock Type	Mineral	Locality	Rb^{87} ppm	Sr^{87} rad. ppm	Sr common ppm	Age m.y.
447-54	Granulite acid	Bi	Anzola, Toce	182	0,502	13,7	187 ± 9
447	Granulite acid	Bi	Anzola, Toce	180	0,490	27,3	185 ± 15
484a	Pegmatite	Mu	Candoglia, Toce	115	0,411	9,1	243 ± 10
504	Biotite Gneiss	Bi	Carmine inf.	107	0,485	4,1	308 ± 7
505	Pegmatite	Mu	SE Candoglia Toce				
506	2-Mica-Gneiss	Bi	Candoglia, Toce	138	0,375	3,1	185 ± 7
507	Biotite-Gneiss	Bi	Omegna, Germagnano	146	0,428	1,5	199 ± 8
558	Biotite-Gneiss	Bi	Valpelline	102	0,276	6,04	184 ± 7
560	Biotite-Gneiss	Bi	Bionaz, Valpelline	177	0,539	8,1	207 ± 8
565	Granite	Bi	Madonna del Sasso				
572	2-Mica-Gneiss	Bi	Mergozzo, Toce	150	0,559	2,3	253 ± 10
599	Granulite acid	Bi	Forno, Strona	46,7	0,133	32,5	193 ± 68
682	Biotite-Gneiss	Bi	Prarayer Valpelline	105	0,293	3,5	190 ± 8
80	Granodiorite	Bi	Camponi, Toce	132	0,368	3,7	189 ± 8
85	Biotite-Gneiss	Bi	Teglia, Toce	147	0,389	1,6	180 ± 7

KAW	Rock Tipe	Mineral	Locality	Rb^{87} ppm	Sr^{87} rad. ppm	Sr common ppm	Sr^{87}/Sr^{86}	Rb^{87}/Sr^{86}	age m.y.
183	Rhyolite	total	Cavagnano	60,2	0,242	25,8	0,8055	23,96	
184	Rhyolite	total	Cavagnano	64,0	0,260	18,0	0,8577	36,61	
908	Rhyolite	total	Bolzano	70,2	0,278	9,2	1,0185	79,05	269 ± 13
909	Rhyolite	total	Romagnano	60,6	0,240	81,5	0,7386	7,637	
910	Rhyolite/ Tuff	total	Romagnano	60,1	0,254	132	0,7291	4,690	

TABLE 1a - K-Ar Data and Age Results on Minerals of the Ivrea and Strona-Ceneri-Zone

KAW	Rock Type	Mineral	Locality	$cm^3 Ar^{40} rad/g$ 10^{-6} STP	% rad.	% K	Age m.y.
504	2-Mica-Gneiss	Bi	Carmine inf.	90,9	95,4	6,96	302 ± 16
504		Mu		104	94,7	7,72	310 ± 16
506	2-Mica-Gneiss	Bi	Candoglia, Toce	58,9	92,0	7,38	190 ± 10
506		Mu		76,1	97,7	8,10	220 ± 11
572	2-Mica-Gneiss	Bi	Mergozzo, Toce	82,0	97,9	7,58	253 ± 13
572		Mu		96,9	98,6	8,23	274 ± 14
				102	52,5	8,23	287 ± 27
682	2-Mica-Gneiss	Bi	Prarayer, Valpelline	53,3	94,9	7,07	180 ± 9
682		Mu		45,0	88,4	8,05	135 ± 8
				45,5	88.8	8.05	137 ± 8
699	Muscovite-Gneiss	Mu	Riva, Valdobbia	65,6	94,5	8,85	177 ± 9
1068	Pegmatite,	Bi	Quarona, Sesia	59,9	94,5	6,76	210 ± 11
1068		Mu		84,3	96,6	8,83	225 ± 9
81	Peridotite	Phl.	Finero	66,5	91,9	7,65	206 ± 9
1222	Peridotite	Ho	Finero	13,5	68,1	0,228	1290 ± 75

This interpretation found in the Lepontine area for an amphibolite facies phase of metamorphism allows one to calculate cooling rates. The Rb-Sr systems where in equilibrium and an initial Sr^{87}/Sr^{86} ratio of the minerals can be calculated, thus giving very accurate ages with low errors.

Already at the borders of the Lepontine where the Eocene/Oligocene phase of metamorphism was only in greenschist facies, the Rb-Sr systems are not any more in equilibrium conditions. The minerals did not exchange their Rb and Sr isotopes completely, so that a calculation of an initial Sr^{87}/Sr^{86} ratio for a given mineral is not possible. The calculated age then represents a maximum cooling age. In the Western Alps conditions are even more complex. In the Ivrea-zone the Hercynian metamorphism was in amphibolite facies and the cooling after this metamorphism very slow.

Muscovites of the Ivrea zone give ages around 210-240 m.y. and biotite ages lie around 170 to 200 m.y., the mean age difference between muscovite and biotite being 40 m.y. A general trend of increasing ages towards the west seems possible, but cannot be proved. A Mesozoic thermal event in the Ivrea zone must be ruled out as we find a slow cooling during this period of around 5° / m.y. In the rest of the Western Alps an early Alpine high pressure-low temperature phase led to disequilibrium of the Rb-Sr system and the later phases of metamorphism only reached greenschist façies, so that again isotopic equilibrium was not attained .During the high pressure phase of metamorphism phengite grew at the expense of K-feldspar. As a consequence this eo-Alpine phengite shows high contents of common Sr adding another complication to the Rb-Sr work in the area. This forced us to work partly with the K-Ar method.

TABLE 2 - K-Ar Data and Age Results on Minerals and Rocks of the Sesia and Canavese-Zone

KAW	Rock Type	Mineral	Locality	cm³ Argon⁴⁰ rad./g 10⁻⁶	% rad.	% K	Age m.y.
414	Pheng. Alkali-feldsparGn.	Pheng.	Lillianes Gressoney	30,3	88,6	8,35	90 ± 5
473	Pheng. Alkali-feldspar Gn.	Pheng.	Quassolo, Aosta	23,4	87,3	8,52	67,7 ± 3,9
474	Pheng. Alkali-feldspar Gn.	Pheng.	Bard, Aosta	22,5	92,4	8,75	63,4 ± 3,4
475	Pheng. Alkali-feldspar Gn.	Pheng.	Barme, Aosta	16,9	88,9	8,86	47,3 ± 2,7
476	Pheng. Alkali-feldspar Gn.	Pheng.	Gattinari Gressoney	22,8	70,0	9,19	61,3 ± 4,4
485	Eclogite	Pheng.	Mucrone, Biella	23,2	96,1	9,29	61,7 ± 3,2
				23,5	94,9	9,29	62,4 ± 3,3
563	Biotite-Pheng. Gneiss	Biot.	Campo, Albino Toce	7,00	74,6	6,23	28,0 ± 2
563		Pheng.		32,9	94,7	8,47	95 ± 5
697a	Andesite	Total Rock.	Favaro, Biella	2,12	62,6	1,58	33,3 ± 2,7
697b	Andesite	Total R	Favaro, Biella	4,24	84,6	3,21	32,8 ± 1,9
698a	Pheng. Gneiss	Pheng.	Favaro, Biella	18,1	90,4	6,19	72,1 ± 3,2
698b	Pheng. Gneiss	Pheng.	Favaro, Biella	24,0	89,3	7,75	76,2 ± 4
912	Tuffite	Pheng.	Sordevolo, Biella	25,6	94,0	8,28	75,9 ± 4
1063	Tuffite	Pheng.	Falletti, Biella	24,5	87,4	7,92	76,0 ± 4,3
1064	Andesite	Total R	Falletti, Biella	5,16	94,0	4,07	31,5 ± 1,3
HA*	Andesite	Total R	Bocchetta Sessera	2,47	82,0	2,05	30,0 ± 1,8
				2,42	80,0	2,04	29,5 ± 1,8
683	Eclogite	Pheng.	Mucrone, Biella	59,2	85,5	8,93	159 ± 10
				58,9	93,1	8,68	163 ± 9
683		Garnet	Mucrone, Biella	1,40	68,0		
683		Omph.		1,45	70,6	0,046	657 ± 37
683		Glauc.		2,60	58,4	0,148	396 ± 27
				2,77	20,3	0,148	420 ± 27
684	Glauc.-Eclogite	Glauc.	Mucrone, Biella	4,56	50,3	0,325	339 ± 34
684		Pheng.		36,9	88,9	8,33	108 ± 6
684		Garnet		0,818	74,0		
685	Phengite Schist	Pheng.	Mucrone, Biella	27,4	87,0	8,50	79,2 ± 2,5
685		Garnet		0,604	58,2	—	—
700	Pheng. Gneiss	Pheng.	Isolello, Sesia	19,0	88,7	9,03	52,1 ± 2,9
989	Pheng. Gneiss	Pheng.	Mucrone, Sesia	24,1	89,2	8,54	71,2 ± 3,2

* Analyses by Teledyne Isotopes Westwood New Jersey USA.

TABLE 2a - Rb-Sr Data and Age Results on Minerals and Rocks of the Sesia and Canavese-Zone

KAW	Rock Type	Mineral	Locality	Rb^{87} ppm	Sr^{87} rad. ppm	Sr common ppm	Age m.y.
415	Biotite-Phengite-Alkalifeldspar-Gneiss	Total	Arnaz Aosta	38,0	0,107	47,1	190 ±125
415	»	Biot.		210	0,111	13,5	36,0± 6,0
415	»	Pheng.		122	0,0839	4,6	46,8± 4,1
473	Phengite-Alkalifeld-spar-Gneiss	Pheng.	Quassolo, Aosta	105	0,258	311	167 ±288
473	»	Total	» »	24,3	0,117	141	330 ±620
474	Phengite-Alkalifeld-spar-Gneiss	Total	Bard, Aosta	27,9	0,221	172	540 ±600
474	Phengite-Alkalifeld-spar-Gneiss	Pheng.	» »	95,3	0,121	46,2	86 ± 60
475	Phengite-Alkalifeld-spar-Gneiss	Total	Barme, Aosta	27,0	0,150	203	377 ±720
475	»	Pheng.	» »	104	0,0675	13,3	44,1± 12,6
476	Phengite-Alkalifeld-spar-Gneiss	Total	Gattinari, Gressoney	18,9	0,0597	67,0	215 ±345
476		Pheng.		62,0	0,0645	24,5	70,7± 38
485	Phengite-Eclogite	Total	Lago Mucrone, Biella				
485	» »	Pheng.	»	94,2	0,0981	12,8	70,8± 13,7

b) K-Ar

PURDY and JÄGER (in prep.) have interpreted Alpine K-Ar ages of rock forming minerals as cooling ages following a phase of metamorphism. The coincidence of Rb-Sr and K-Ar data of biotite led them to set the closing temperature at 300°C for the K-Ar system of biotite under regional metamorphic conditions. The K-Ar muscovite ages lying between the Rb-Sr muscovite and biotite ages, are interpreted to represent a closing temperature of 380°C according to J.W. PURDY and E. JÄGER (in prep.).

This interpretation, valid for the Lepontine area, also holds for the Ivrea-Verbano and the Strona-Ceneri zone. For the rest of the Western Alps difficulties resulted from the high pressure low temperature phase of metamorphism, because it was never sure to what extent apparent ages represented true ages and were not just due to inherited argon. To establish reliable criteria for a distinction $Argon^{40}/Argon^{36}$ ratios of K-poor to K-free minerals such as garnets, chloritoid, chlorites and zoisites were measured. Also the data where plotted on isochron plots (K^{40}/Ar^{36} versus Ar^{40}/Ar^{36} and Ar^{40} rad. versus K^{40}.

The result of this approach was that normal initial values were found only in the Alpine metamorphic Mesozoic schistes lustrés or in other words apparent ages represent true ages. In the pre-Triassic basement of the Sesia-Lanzo zone and of the Briançonnais-Bernhard nappe Ar^{40} accummulated since the Hercynian event and was not completely released during the early Alpine high pressure event. There the apparent ages represent argon overpressure strongly depending on the degree of schistosity of

TABLE 3 - K-Ar Data and Age Results of Minerals of the Pennine Region

KAW	Rock Type	Mineral	Locality	cm^{-3} Ar^{40}rad/g 10^{-6} STP	%rad.	% K	Age m.y.	Ar^{40}/Ar^{36}	$K^{40}/Ar^{36} \times 10^3$
653	Eclogite	Ch. toid.	Pfulwe	,141	1,6	nd	—	291,6	—
653		Parag.		,713	21,9	,519	34,1 ± 6,2	387,5	44,96
				,576	9,5	,519	27,6 ± 11,6	332,3	18,58
655	Eclogite	Ho.	Pfulwe	,0256	1,6	,032	19,8 ± 62	308,0	4,36
655	Eclogite	Glauk.	Pfulwe	,014	6,3	,049	7,2 ± 4,6	310,3	20,25
655		Parag.		,647	25,0	,353	45,4 ± 9,1	390,3	34,59
655		Gar.		0	0	,005	—	295,8	2,45
655		Omph.		0	0	,008	—	302,8	2,92
656	Eclogite	Glauk.	Pfulwe	0	0	nd	—	298.8	—
657	Eclogite	Glauk.	Pfulwe	,411	41,6	,130	77,9 ± 9,3	500,7	46,90
657		Parag.		,916	32,4	,616	36,9 ± 6	425,6	68,10
				,906	16,6	—	36,5 ± 11	364,0	28,49
657		Gar.		0	0	,020	—	293,1	7,26
657		Ho.		,460	53,7	,066	168 ± 16	663,4	35,20
658	Ho.-Ab. vein	Ho.	Pfulwe	1,05	44,8	,089	274 ± 25	550,1	15,32
661	Prasinite	Glauk.	1 Pfulwe	,155	6,9	,016	235 ± 170	308,1	1,36
661		Glauk.	2	,020	4,5	,016	31 ± 35	318,7	1,57
				,032	8,5		53 ± 31	319,4	4,55
661		Gar.		0	0	,009	—	305,1	3,93
661		Parag.		,056	2,3	,136	10,4 ± 18	307,6	4,47
661		Chl.		0	0	,017	—	297,2	1,00
750	Glauk. Schist	Glauk.	Ollomont	,087	15,8	,045	48,1 ± 15	345,2	17,15
				,0053	4,6	—	29,4 ± 32	319,7	7,67
792	Eclogite	Glauk.	L. Cignana	,080	17,4	,096	20,9 ± 4,8	374,2	40,65
794	Glauk. Schist	Glauk.	Ulcio	,132	14,6	,045	74,2 ± 2,5	354,9	11,09
				,148	12,3	—	81 ± 33	344,6	7,99
943	Glauk. Pheng. vein	Glauk.	M. Gelé	4,37	88,3	,461	224 ± 13	2673	187,0
943		Pheng.		38,22	96,3	6,44	143 ± 6	8358	1030
1117	Epidote Amphibolite	Glauk.	Rimpfisch-horn	,803	53,7	,419	47,4 ± 3,5	664,7	140,3
1118		Glauk.	Alp Pilaz Valtour-nanche	,0166	1,3		11 ± 33	310,4	2,49
1120	Ho Prasinite	Ho.	Mellichen Täschtal	,281	28,3	,322	21,7 ± 3	433,0	102,3
1121		Omph.		,301	31,7	,114	65,0 ± 8,2	451,0	40,0
1122	Epidote Amphibolite	Ho.	Stock-knubel	,516	52,3	,331	38,7 ± 3,0	661,2	166,5
		Parag.	Pfulwe, Zermatt	,738	21,3				
1217	Ep. Amphibolite	Amph.	Loranco	,267	13,1	,248	26,8 ± 10	346,9	28,11
1218	Prasinite	Amph.	Loranco	,620	31,4	,172	88 ± 14	440,3	27,74
1219	Ho.-Ab.Omph.Fels	Amph.	Stock-knubel	,563	6,6	,315	44,3 ± 33	320,4	8,38
1221	Gar. Amphibolite	Amph.	Loranco	1,186	63,1	,291	99,5 ± 8	855,8	95,76
1220	Marble	Amph.	Furgg-Tal	,473	43,8	,233	50,2 ± 5,7	530,8	81,70
1124		Omph.		0	0	,007	—	304,3	1,93

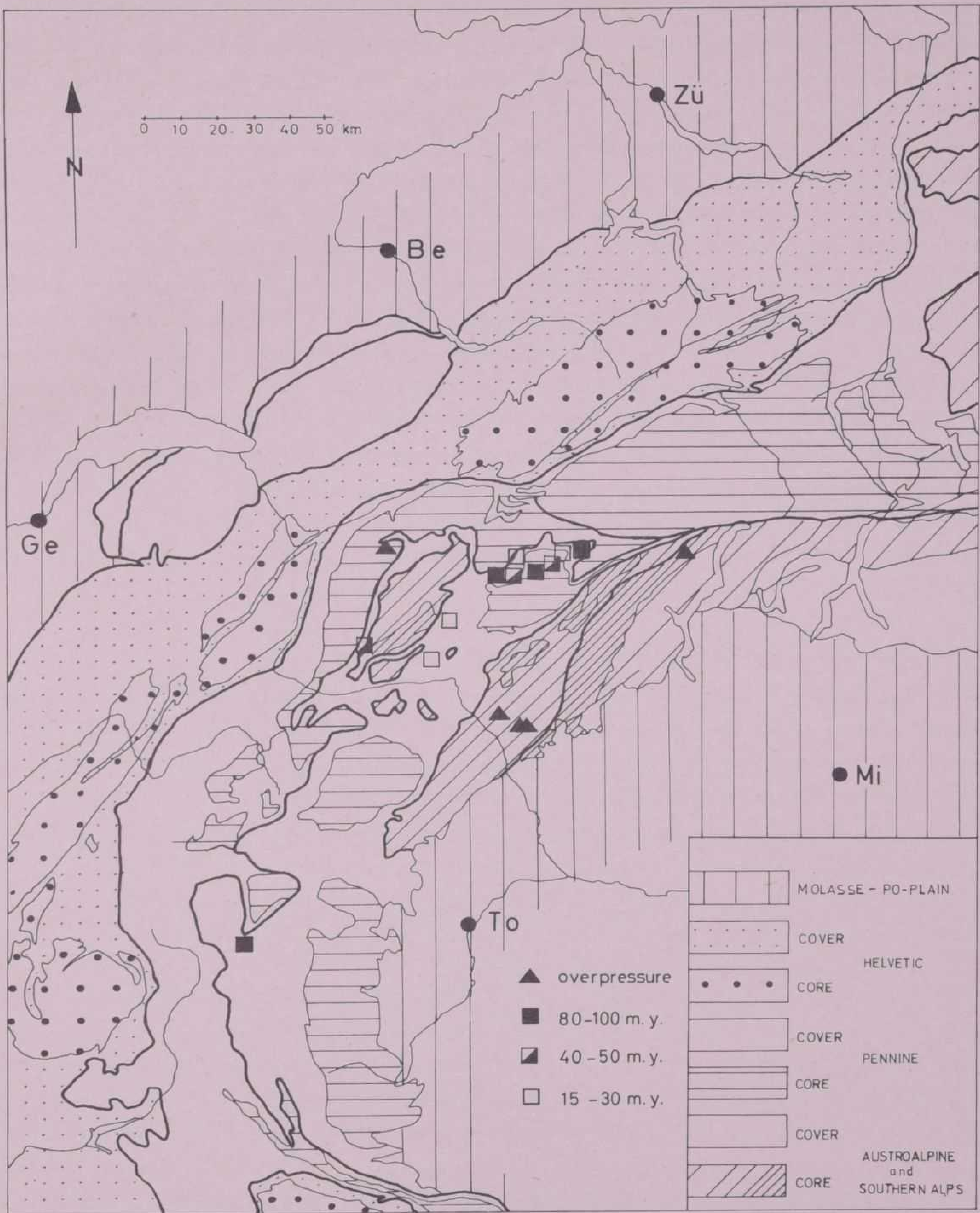

FIG. 2 - Tectonic sketch map of the central and western Alps (as Fig. 1) with the distribution of the analyzed amphiboles.

the rocks. Schists show lower ages than massive rocks. Argon overpressure goes together with high measured contents in CO_2. The problems of argon overpressure can best be shown by means of isochron plots.

In the literature 2 kinds of argon isochron plots are found, the Ar^{40}/Ar^{36} versus K^{40}/Ar^{36} and the Ar^{40} rad. versus K^{40} plot. For a critical discussion see HARPER (1970), HAYATSU and CARMICHAEL (1970) and RODDICK and FARRAR (1971).

The disadvantage of the Ar^{40} rad. versus K^{40} isochron plot is, that only with different minerals a good spread on the K^{40} axis is attained. Normally good unweathered micas have only a very small spread in their K-content; therefore the phengites were plotted on an Ar^{40}/Ar^{36} versus K^{40}/Ar^{36} plot. Normal amphiboles are often found on Ar^{40} rad. versus K^{40} plots. In this study the spread in the K-content of the alkali-amphiboles was too narrow to allow a compilation on a Ar^{40} rad. versus K^{40} diagram, again forcing us to use the Ar^{40}/Ar^{36} versus K^{40}/Ar^{36} isochron. Roddick and Farrar have shown that a contamination with residual argon of the line can change the Ar^{40}/Ar^{36} ratios with changing percentage of radiogenic argon. These authors proposed that only samples with more than 95 % radiogenic argon should be plotted on a Ar^{40}/Ar^{36} versus K^{40}/Ar^{36} plot. This statement is only valid when the initial $Ar^{40}/^{36}$ ratio of an isochron is not equal to the ratio of air argon and or if the amount of Ar^{36} measured comes out of the line and not out of the sample. In the first case the possible contamination is not seen and the second case is not valid for our samples with high initial Ar^{40}/Ar^{36} values e.g. the Alpine eclogites in the pre-Alpine basement. In these samples the contamination with residual argon of the extraction system is only in the order of magnitude of 1 to 5 % and therefore (within the error limits) does not affect the 40/36 ratios.

c) *Anomalously high Ages, a Case of Argon Overpressure?*

Some apparent K-Ar ages of this work show either a big scatter over a small distance or are much to high in terms of the geologic evidence. It can be shown that these high ages are due to argon overpressure, or inherited argon, and it seems that high pressure mineral assemblages are particularly susceptible to argon overpressure.

The peridotite of Finero in the Ivrea zone contains phlogopite and hornblende in places. In agreement with the biotite ages of the Ivrea zone, the phlogopite gives a Rb-Sr age of 180 m.y. (Table 1 and Plate I). D. Krummenacher (1960) determined a K-Ar age on the same mica of 246 m.y.. This age alone would not justify speaking of argon overpressure in these rocks.

The hornblende of the Finero peridotite has yielded an age of 1300 m.y., a value not previously found in the Alps and difficult to explain otherwise than through argon overpressure. Plotted on a Ar^{40} rad./K^{40} diagramm (Fig. 3), both hornblende and phlogopite give an age of 180 m.y. in good agreement with the Rb/Sr age and also with F.W. McDowell and R. Schmid (1968) giving an age of 208 m.y. for a hornblende from a metagabbro of the Ivrea zone.

The alkali-amphiboles of the Pennine eclogites give an Ar^{40}/Ar^{36} to K^{40}/Ar^{36} isochron plot of 80-100 m.y. with a normal initial ratio Ar^{40}/Ar^{36} of 290,5 (Fig. 12). An examination of the Ar^{40}/Ar^{36} ratios of potassium-poor minerals coexisting with these alkali-amphiboles (i.e. garnet, omphacite, chlorite, chloritoid and amphiboles) give Ar^{40}/Ar^{36} ratios of 290 - 310 (see Table 3). The contribution of radiogenic argon being unimportant, no sign of argon overpressure is noted. The Ar^{40} content in these potassium-poor minerals is in the range of 0,5 - 2,0 x 10^{-6} cm^3 Ar^{40}/g S.P.T. and the blank for the extraction system is about 2 x 10^{-8} cm^3 Ar^{40}/g S.T.P.

We think that the contribution of the blank to these values is negligible and that we measured initial Ar^{40}/Ar^{36} ratios in the Mesozoic eclogites.

The Austroalpine eclogites are quite different. They occur in an Alpine metamorphic pre-Alpine basement, and argon released by the Alpine metamorphism, and incorporated in the high pressure rocks as inherited argon, can be expected.

This difference was already noticed in the measurements of phengites, their apparent ages varying from 62 to 95 m.y., in two instances even up to 160 m.y. (Table 2). As we have the two different estimates for the time of metamorphism

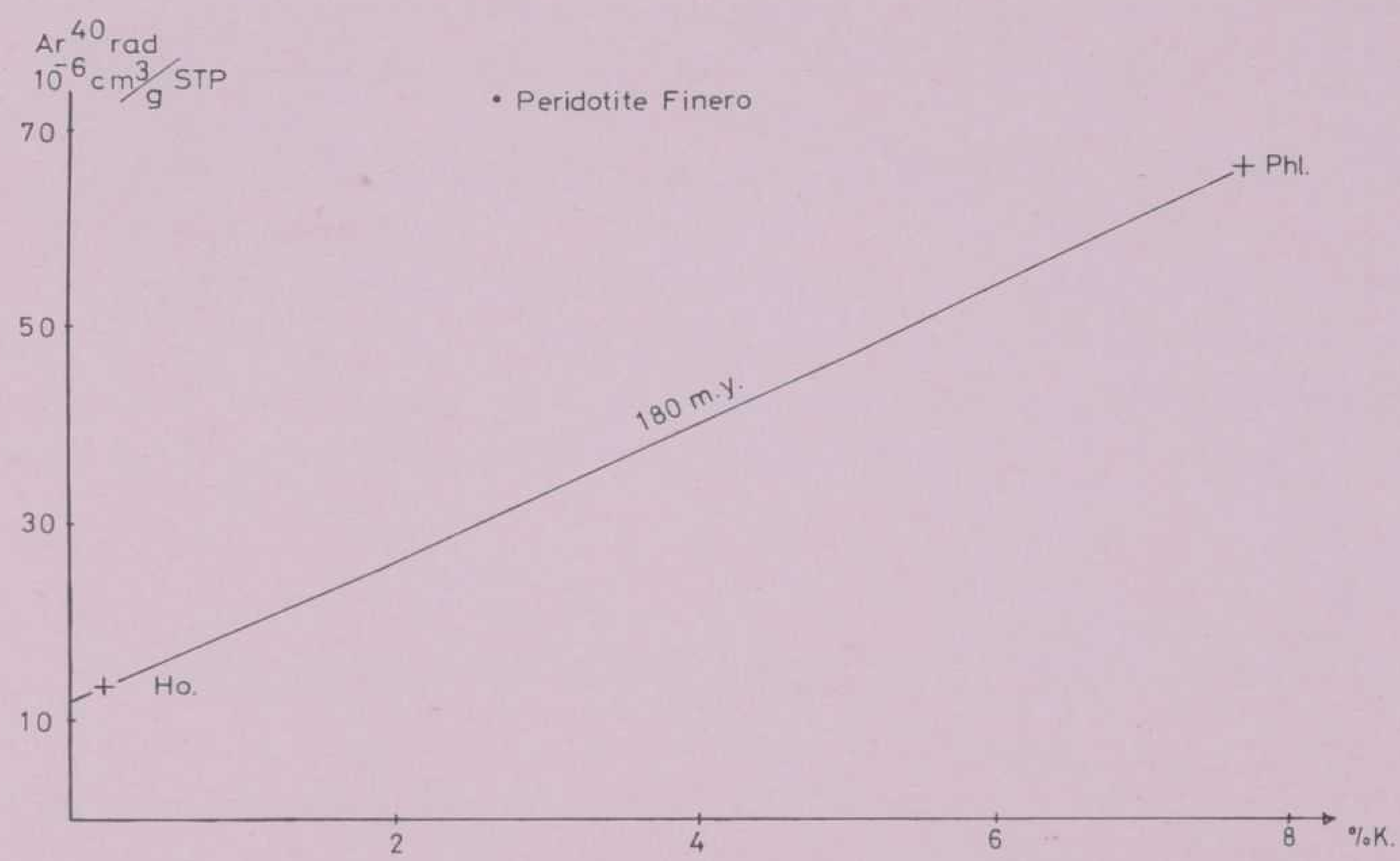

FIG. 3 - Ar^{40} rad. versus K^{40} isochron plot of the peridotite of Finero.

with the Pennine alkali-amphibole K/Ar apparent ages of 80-100 m.y. and a phengite K/Ar isochron of the Sesia zone indicating an age of around 60 m.y. (Fig. 8) close to the Rb-Sr ages measured on the same micas (around 70 m.y.) we must find the explanation in the different histories of Pennine and Sesia-zone.

In the Sesia-zone we had the beginning of the high pressure metamorphism around 80-100 m.y.. The temperature increase came to a maximum of around 300°C, 20 m.y. later. During or immediately after this temperature maximum the phengites became closed systems.

In the Pennine region the first high pressure phase around 80-100 m.y. was followed by a second phase of nappe movement and compression at the Eocene/Oligocene boundary. The temperature was built up steadily reaching its climax around 40 m.y. producing mica ages of 40 m.y. and younger (Fig. 18).

The ages of 95 to 160 m.y. seem rather high. One eclogite lense from Lago Mucrone in the Sesia-zone was examined carefully and gave a great amount of information. The center of the eclogite lense is composed of practically untransformed eclogites (garnet, omphacite and a little alkaliamphibole and phengite (KAW 683 = a). The rim (KAW 684 = b) of the same lense contains far more alkali-amphibole, phengite and zoisite are common. The proportion of omphacite is much lower than

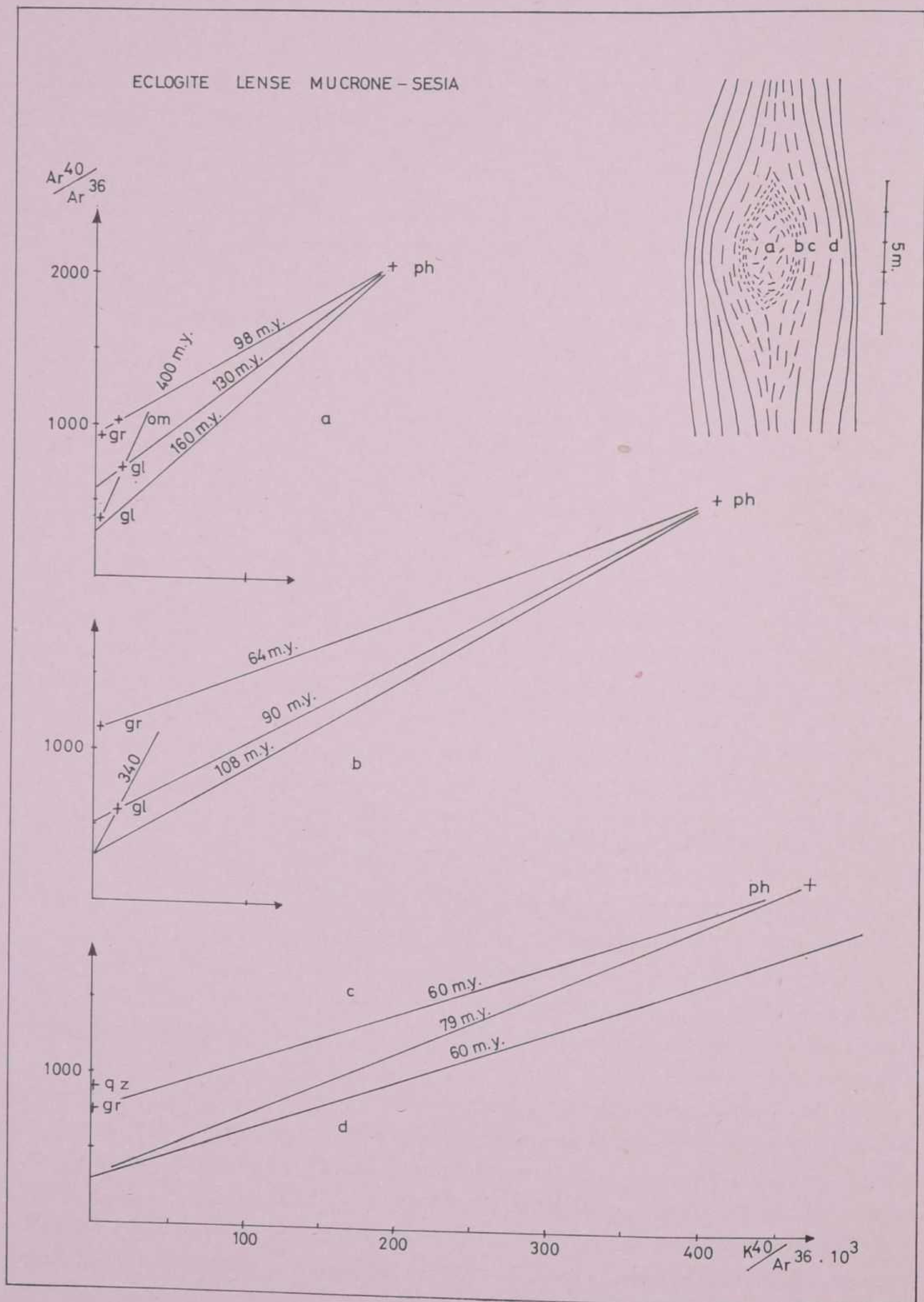

FIG. 4 - Ar^{40}/Ar^{36} versus K^{40}/Ar^{36} isochron plots of an eclogite lense at Mucrone Sesia zone, showing the great amounts of inherited argon incorporated in the potassium poor minerals as garnet, omphazite and glaucophane. The strong disequilibrium does not permit the interpretation of true ages.

in the core and the parallel texture much more intense. The outermost rim is a micaschist containing alkali-amphibole and garnet (KAW 685 = c). The apparent K-Ar phengite ages of a, b, c are 160, 108 and 79 m.y. (Fig. 4). A few meters away, sample KAW 485 = d yielded a phengite age of 62 m.y.. The co-existing alkali-amphiboles gave ages of 400 and 340 m.y.. The initial Ar^{40}/Ar^{36} ratios of the garnets are 925 and 1150 showing that this is another case of excess argon. After correction with the initial Ar^{40}/Ar^{36} values we obtain phengite ages of 64 respectively 98 m.y.. The extent to which the initial argon of the garnets in the first metamorphic generation was exchanged during the consecutive transformation from eclogite to glaucophane schists is not known.

The negative alkali-amphibole ages show that in this case a correction for initial Ar^{40}/Ar^{36} is not possible.

The conclusion of the study of excess argon is that potassium — poor or even potassium — free minerals such as garnets, chloritoids, chlorites, quartz etc. can be used to check initial argon ratios of a rock, but only in cases where equilibrium was attained, is a correction for initial overpressure possible.

IV. CONFRONTATION OF GEOCHRONOLOGY WITH GEOLOGY

1) The Austroalpine Domain

a) *Ivrea-Verbano and Strona-Ceneri-zone*

At the beginning of this century Italian geologists had worked out the following age relations in the Southern Alps. A series of paragneisses and intercalated basic and ultrabasic rocks was metamorphosed partly in granulite- and partly in amphibolite facies in pre-Permian time. This metamorphic complex is cut by Permian granites and rhyolites. The contact aureole of the granites clearly demonstrates this age relationship (Artini and Melzi (1900), Novarese (1906), Franchi (1906)), (Fig. 5).

The unconformably overlying Triassic sediments give a minimum age for the volcanics which according to field relationships are of the same age as the granites. This picture was confirmed by various radiometric age determinations (Fig. 5).

The Permian age of the rhyolites, porphyries, tuffs is demonstrated by a Rb/Sr whole rock isochron with an age of 269 ± 13 m.y. and an initial Sr^{87}/Sr^{86} ratio of 0,710 ± 0,004 (Fig. 6). Jäger and Faul (1959) have shown that the Baveno-granite suite is also Permian. Rb/Sr and K-Ar mineral ages vary between 268 and 275 m.y.. Pasteels (1964) found slightly discordant U/Pb zircon ages of 253 to 273 m.y. and Köppel (1974) found concordant U-Pb ages of monazite at 295 ± 5 m.y.. Graeser and Hunziker (1968) published a total rock isochron based on bands of a granulite of the Ivrea zone, giving an age of 310 ± 60 m.y. with an initial Sr^{87}/Sr^{86} of 0,717 ± 0,002. The high initial ratio and the exchange of main components and trace elements between the bands lead us to the conclusion that we had dated a metamorphic event. The Hercynian total rock isochron was also interpreted as giving a minimum age for the emplacement of the upper mantle wedge causing the geophysical discontinuities of the zone.

The decrease of metamorphism towards the South, ranging from granulite facies to amphibolite facies (SCHMID 1967), is similar to a cross section through the crust, from the Upper Mantle / Crust transition zone upward.

Today this cross section is tilted into the horizontal i.e. the once horizontal layering is vertical. The northernmost regions could represent crustal depths of around 40 km. That the basic and ultrabasic rocks can really be derived from Mantle material is not only evident through the trace lead analysis by GRAESER and HUNZIKER (1968), giving low μ values of around 8,9 but also by the K/Rb and Rb/Sr ratios. ARMSTRONG (1968) gives a K/Rb ratio of greater than 1200 for the Upper Mantle and of 300 for the crust. The basic and ultrabasic rocks of the Ivrea zone have K/Rb ratios around 5000. The same author quotes Rb/Sr ratios of 0,01 for the Upper Mantle and 0,15 for crustal rocks. Also here these rocks with a Rb/Sr ratio of about 0,01 lie definitely in the field of Upper Mantle rocks. The Sr^{87}/Sr^{86} ratios measured until now being around 0,706 (normalized with 88/86 = 8,375) are rather high for Upper Mantle rocks, therefore more work on this problem is required.

KÖPPEL (1974) observed drastic lead losses in zircon populations of granulite facies rocks 285±10 m.y. ago, whereas the monazites yielded concordant U-Pb ages of 275±2 m.y.. The zircon age pattern of a neighbouring migmatite zone indicates that the metamorphism of the Ivrea zone rocks may have occurred, or may have started 450 m.y. ago. ZWART (1967) considers a Caledonian granulite facies metamorphism to be more plausible, and work on this problem is therefore still continuing.

The Hercynian metamorphism of the Ivrea-zone corresponds with the last metamorphism of the Strona-Ceneri zone to the south, where K-Ar mineral ages have been reported by McDOWELL (1970) in the range of 270-320 m.y.. His hornblende ages of up to 390 m.y. and the zircon data of Pidgeon et al. (1970), KÖPPEL and GRUENENFELDER (1971) show that in the Strona Ceneri zone a strong isotopic disturbance must already have occurred before the Hercynian metamorphism around 450 m.y. We find no traces of metamorphism in the Strona-Ceneri zone younger than the Hercynian event. On the other hand, the Ivrea-zone, which according to SCHMID (1972) has the same sedimentary history as the Strona-Ceneri-zone, shows younger mineral ages around 200 ± 30 m.y. (GRAESER and HUNZIKER (1968), McDOWELL and SCHMID (1968), McDOWELL (1970) and Plate I and II). All the analyzed biotites of the Ivrea-zone show K-Ar and Rb-Sr ages between 170 and 210 m.y., the corresponding muscovites being about 30 m.y. older. GRAESER and HUNZIKER (1968) have discussed the two possibilities of the thermal history of the Ivrea-zone in terms of a two pulse or a single event model (Fig. 7). For the time span between 300 and 180 m.y. we have more evidence for a slow lifting and cooling of the zone than for a two stage model (one event Hercynian and one around 180 m.y.). The big age difference between muscovite and biotite, being at least five times bigger than in the Central Alps during the post Alpine cooling

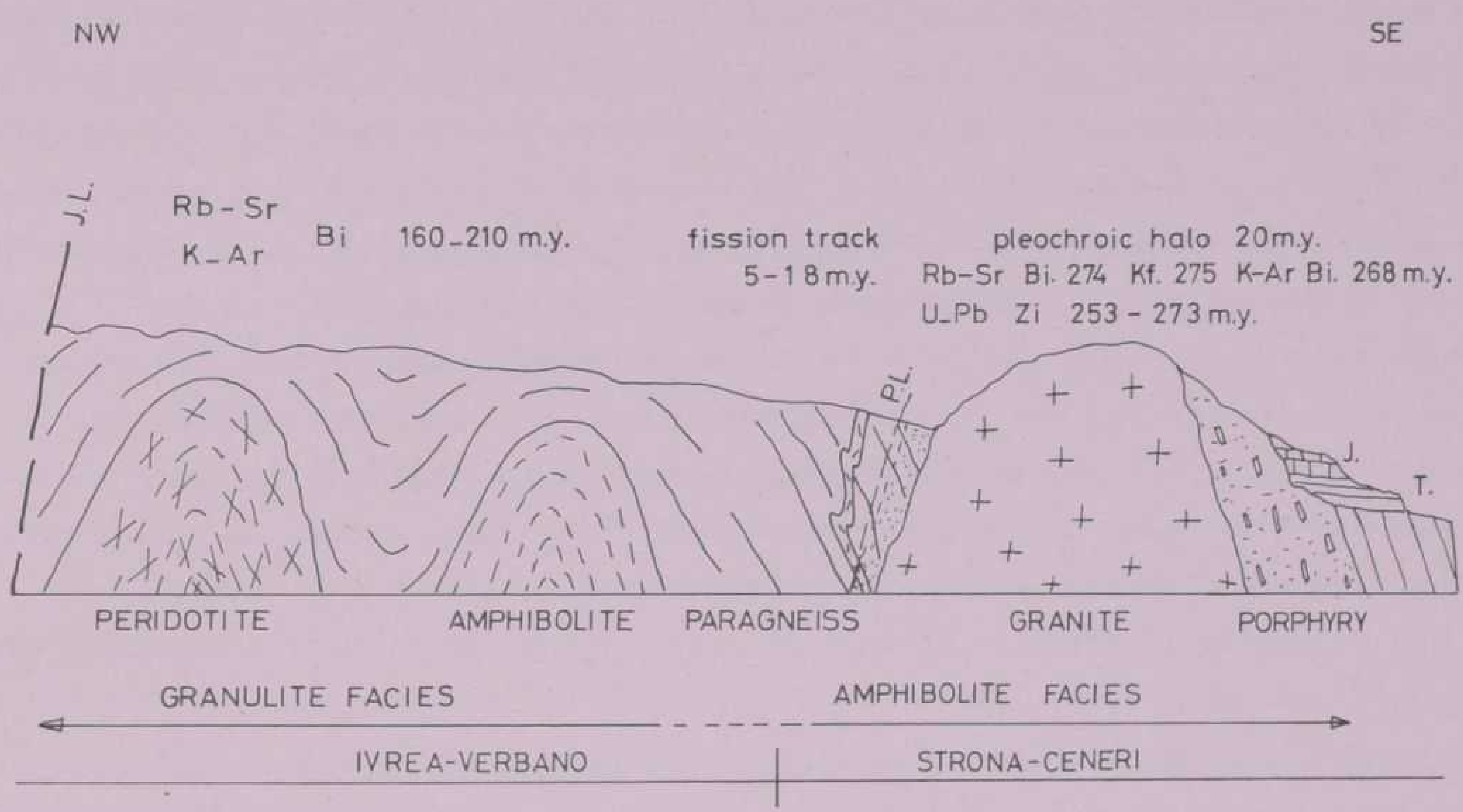

FIG. 5 - Generalized profile through the Strona Ceneri and Ivrea-Verbano zone with age determinations of the literature. IL = Insubric Line, PL = Pogallo Line.

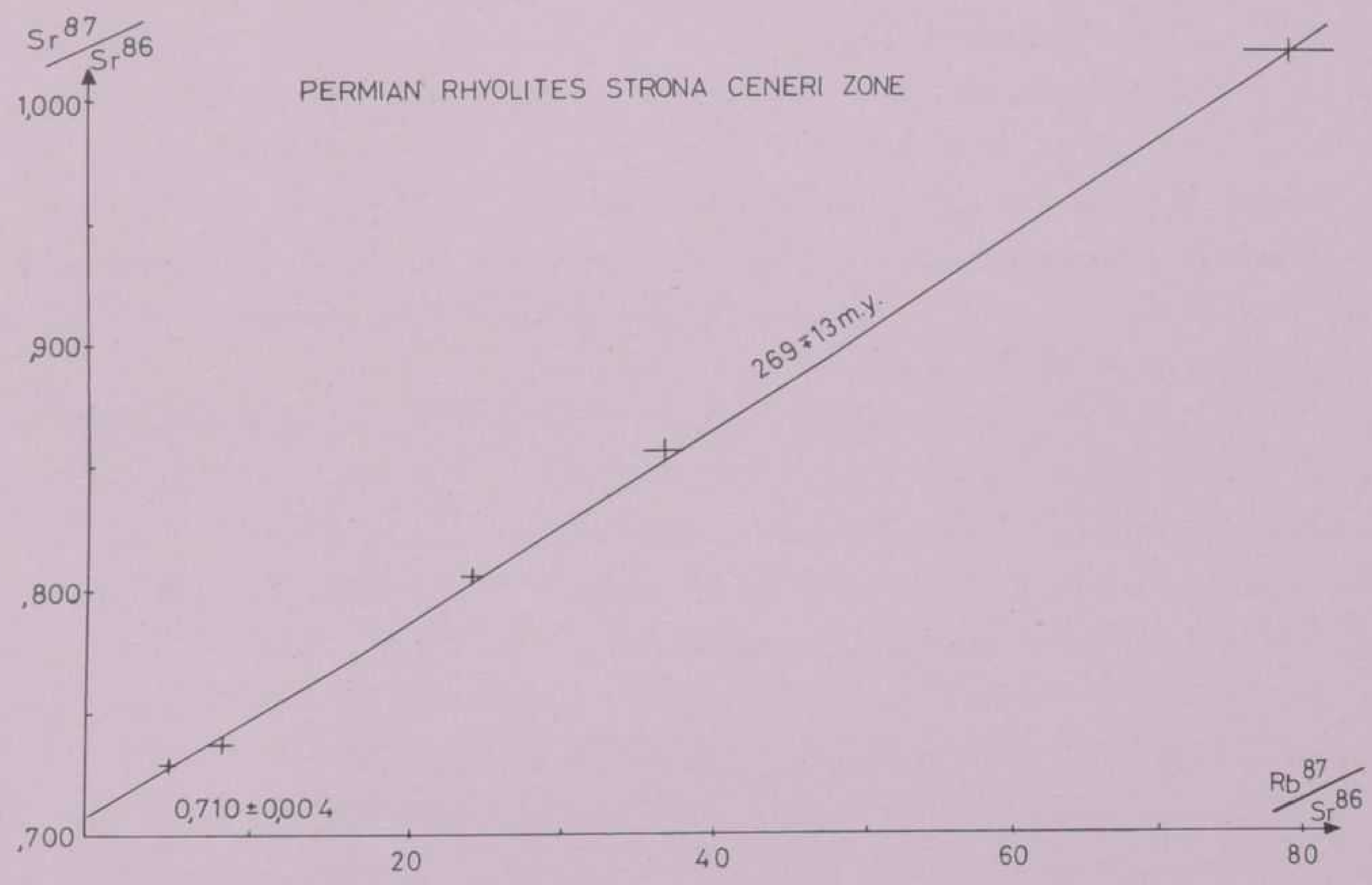

FIG. 6 - Rb-Sr total rock isochron of Permian porphyries rhyolites and tuffs of the Strona Ceneri zone.

(CLARK and JÄGER (1969)) suggest a very slow cooling of the Ivrea-zone around 200 m.y.. The 270 m.y. old intrusive granodiorites (KAW 80 granodiorite of Camponi, Toce) show no contact aureole at all, so that the country rock must still have been quite hot, thus allowing to draw a straight line of temperature decrease (as simplest model) between around 300 and 180 m.y..

The next temperature mark is found in the Jurassic to Lower Cretaceous sedimentary cover of the Canavese, where according to HUNZIKER and ZINGG (in preparation), the index of the cristallinity of illite marks the transition between non-metamorphic and anchimetamorphic, or about 200°C. As the Tertiary sediments of the cover did not reach this grade of metamorphism, the time of the event must be Upper Cretaceous. The next temperature mark is given by the fission track data of PASTEELS (1960), MILLER and JÄGER (1968) of WAGNER and RAIMER (1972) giving a minimum temperature of about 100°C. The simplest model would be the connection of all these points through a straight line representing a slow cooling of about 2°C/m.y.. The possibility of a cooling during the Cretaceous, a reheating during the upper Cretaceous phase and during the Lepontic phase cannot be ruled out (dotted lines), but there is no evidence for this more complex model. Alpine movements were restricted to vertical and or minor horizontal movements along fault zones, for example the pre-Alpine/Alpine Insubric line system (JOHNSON (1973)).

The remaining problem is the age of emplacement of the upper mantle wedge under the Ivrea-zone.

The slow and undisturbed sedimentation throughout the Jurassic and lower Cretaceous in the Southern Alps (BERNOULLI, 1972) together with the slow cooling of the basement during the Mesozoic excludes this time span. An emplacement in pre-Alpine times leads to severe complications, as it would have to be set as far back as the Hercynian or even further. The emplacement of the upper mantle wedge could be connected with the proposed tilting of the whole once vertical profile into the present horizontal position with granulite facies in the north and amphibolite facies in the south. This tilting must have occurred at least 300 m.y. ago as the granites have contact halos crossing the borders Strona-Ceneri to Ivrea-Verbano zone thus showing that the present position of the two zones has not been changed since the Permian. In addition myarolitic cavities in the granites become more abundant towards the upper parts of the granites.

The relict Carboniferous sediments beneath the Permian porphyries are subhorizontal and show only a slight Alpine tilting towards the Po-plain (10°-20°) showing that the main tilting of the zone must have occurred earlier.

A connection between the Hercynian or older tilting of the Ivrea-Verbano zone from vertical to horizontal with the emplacement of the Upper Mantle wedge would implie that the gravity anomaly of the order of magnitude of the Ivrea anomaly would persist over 300 m.y., a rather unprobable assumption.

The plausible possibility remaining is an emplacement linked with the Upper Cretaceous phase of metamorphism and tectonics in the Western Alps.

b) Canavese zone

The adjacent Canavese zone consists of basement rocks — the phyllonitized scisti di Fobello e Rimella — derived partly from rocks of the Ivrea and partly from the Sesia-zone (ARTINI and MELZI, 1900). A stratified sequence is found, which includes acid volcanics and sediments ranging from Upper Permian to fossiliferous lower-Cretaceous, the lower boundary is non-fossiliferous and therefore uncertain. Granites of uncertain intrusive relationship to these stratified rocks mentioned occur (AHRENDT, 1972). Strong vertical movements in Liassic times are manifested throughout the South Alpine area as Triassic faults are filled with Lias (F. WIEDENMEYER, 1963 and

AHRENDT, 1972). In addition to the Permean or Triassic acid volcanism, volcanic rocks mainly of andesitic composition, are widespread. The latter volcanics have already been described as porphyrites by B. GASTALDI (1871), NOVARESE (1929), FRANCHI (1905), ARGAND (1916, 1934), BIANCHI and Gb. DAL PIAZ (1963). These rocks are mostly fresh and well preserved. In the vicinity of the Insubric line, a tectonic overworking can often be seen but in some cases is also absent (Gb. DAL PIAZ personal communication and AHRENDT (1972).

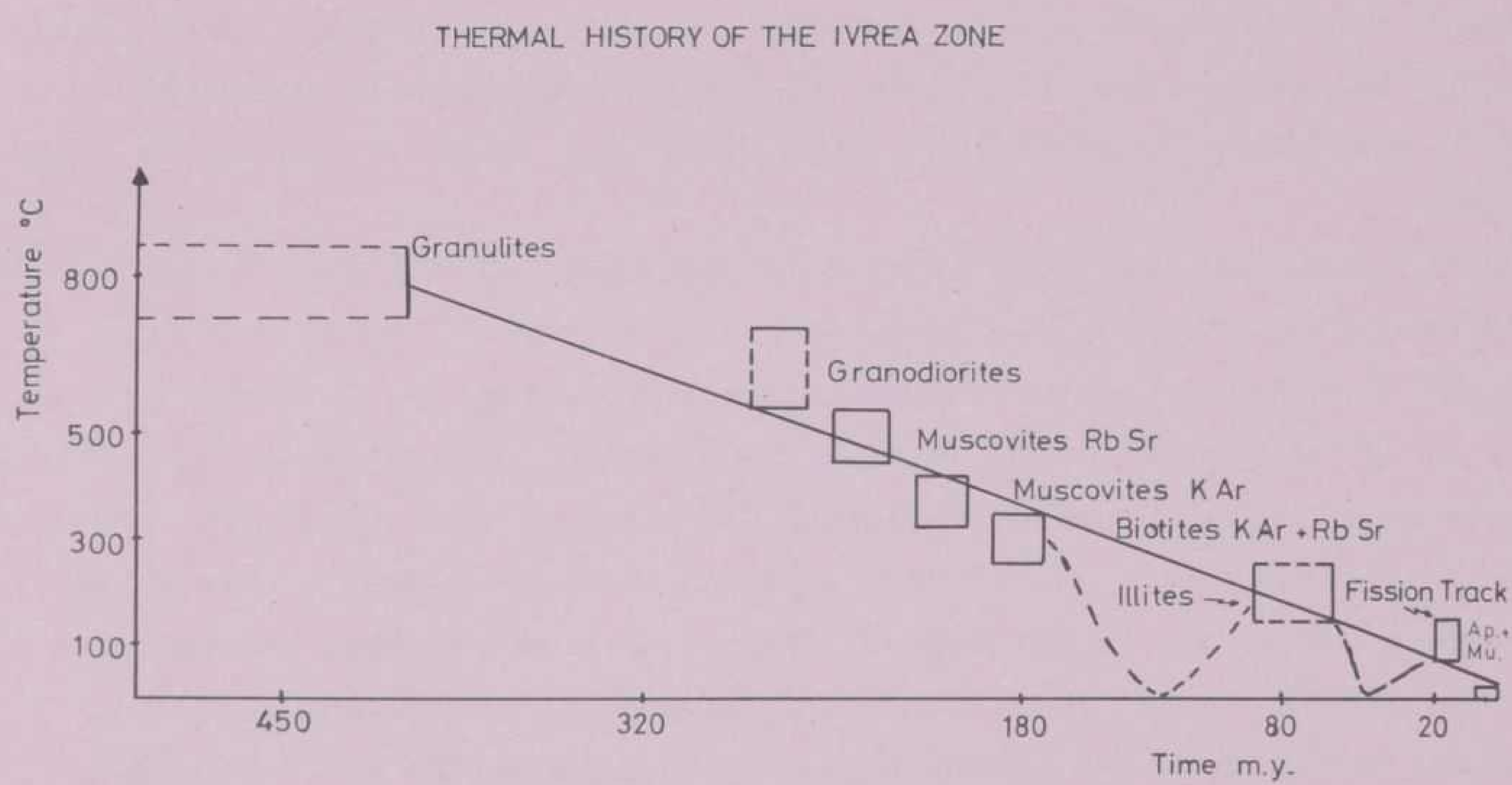

FIG. 7 - Thermal history of the Ivrea zone showing the slow cooling between Permian and Liassic. □ Fixpoints of age determination; |‾ ‾ ‾| probable points.

Making an analogy with the Permian volcanics of the Southern Alps, all the Italian authors have argued for a Permian age for the andesites in the Canavese. BIANCHI and Gb. DAL PIAZ (1963) describe blocks of the Sesia basement in these volcanic rocks at Favaro, near Biella. They proved that the metamorphism of the inclusions in the andesites is the same as that in the Sesia gneisses which contain eclogites composed of omphacite, garnet, alkali amphibole and phengite. This argument leads to the conclusion that the metamorphism in the Sesia-zone is pre-Alpine. CARRARO (1966) described a detrital sequence as Upper Carboniferous because it was underlying the andesites. CARRARO and CHARRIER (1972) found fossils in this sequence which they identified as of Carboniferous age. So far the general picture of the Canavese zone is quite unambiguous. The first doubts about the age of the metamorphism arose when the micas of the Sesia zone turned out to be Alpine. AHRENDT (1969) on tectonic arguments, concluded that the andesites must be of Tertiary age, a possibility already discussed by REINHARDT (1966). SCHEURING et al. (1974) came to the conclusion that the andesitic volcanism must be Tertiary. Detrital micas in tuffites and micas from the basement inclusions in the volcanites have eo-Alpine [1] ages of 60 - 90 m.y. (Table 2 and Plate II).

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[1] Eo-Alpine as proposed by G.V. DAL PIAZ *et al.* (1972) for the Upper Cretaceous phase of Alpine tectonics and metamorphism in eclogite to blueschist facies.

These ages were found in the two separate sedimentary sections described by CARRARO as Upper Carboniferous.

SCHEURING *et al.* (1974) showed that the tuffites still contain basic plagioclase and K-feldspar. The plagioclase has an An content between 41 and 60 mol. % An and the ratio K-feldspar to plagioclase is around 1. The rather high content of K-feldspar in some samples places the rocks in the trachyandesites-andesite group, according to STRECKEISEN (1967). By means of X-ray work ($\Delta\Theta = 2\ \Theta_{131} - 2\ \Theta_{1\bar{3}1}$ (CuK α 1)) of plagioclase SCHEURING *et al.* could show that the properties of the plagioclase (andesine - labradorite) are still those of high to intermediate temperature. Both observations show clearly that the samples are unmetamorphosed. Temperatures of as low as 200°C would have transformed the plagioclase into albite according to COOMBS (1961).

This means that the tuffite must be younger than 60 - 90 m.y.. Total rock K-Ar determinations on four samples of andesites yield ages of 29 - 33 m.y. (Table 2) and prove the Oligocene age of this volcanism. In addition pieces of wood, sporae and pollen out of interlayered tuffites prove a Tertiary age. This Tertiary basic volcanic province seems to follow the south side of the Insubric line generally (AHRENDT, 1972 and PICCOLI, 1958, 1961, 1964, 1966a and b, 1971) and ranges in age from Paleocene to Oligocene. In the light of the new data, the Western extension of these rocks should be compared once more with the widespread volcanic inclusions of the Taveyanaz sandstone of the Prealps for a possible connection in their origin.

The coincidence in the ages of the effusive and intrusive rocks on both sides of the Insubric line enables us to estimate the amount of movement along the line since the Oligocene. K-Ar and Rb-Sr ages of biotite from the Biella and Traversella Syenite lie between 28 and 31 m.y.. These ages represent the time of the cooling of the intrusion. As we are only dealing with rather small stocks intruded at shallow depths of about 2 km, the age of the intrusion is most likely to be only slightly older (KRUMMENACHER and EVERNDEN (1960), HUNZIKER and BEARTH (1969). It is of interest to note that CARRARO and FERRARA (1968) described an Alpine tonalite south of the Insubric line, giving biotite Rb-Sr and K-Ar ages of 29 to 33 m.y.. The andesites with ages from 29 to 33 m.y. occur as flows between the syenite and tonalite mentioned above. The roof of the « syenite » of Biella outcrops about 2000 m above sea level (a.s.l.) today, and the overburden is estimated to have a minimum thickness of 2 km. As the andesite is found only 500 m a.s.l., we can assume a vertical dislocation of at least 3,5 km along the Insubric line since the Oligocene.

c) *Sesia-Lanzo-zone*

The Sesia-zone consists of three main elements. The north-western part towards the Pennine Mesozoic Bündner Schiefer basin is mainly composed of alkali feldspar phengite-gneisses: the Gneiss Minuti of the Italian Geologists. The part adjacent to the Insubric line is known for the widespread occurence of eclogites in phengitic and muscovitic micaschists (VITERBO-BASSANI and BLACKBURN, 1968). The Italian geologists call this zone Micascisti Eclogitici (BIANCHI and Gb. DAL PIAZ, 1963). A third unit of the Sesia zone includes Ivrea type rocks and is mainly allochthonous; only in the northeastern Sesia zone is this Seconda Zona Diorito-Kinzigitica also known as an autochthonous mass (ZINGG, 1971, ISLER and ZINGG, 1974, G.V. DAL PIAZ *et al.*, 1972 + 73).

According to FIORENTINI - POTENZA and MORELLI (1968), FIORENTINI - POTENZA (1969) and FREY *et al.* (in pre-paration), VELDE and KIENAST (1973), the white micas of the Sesia-zone are mainly phengite, but muscovite and even

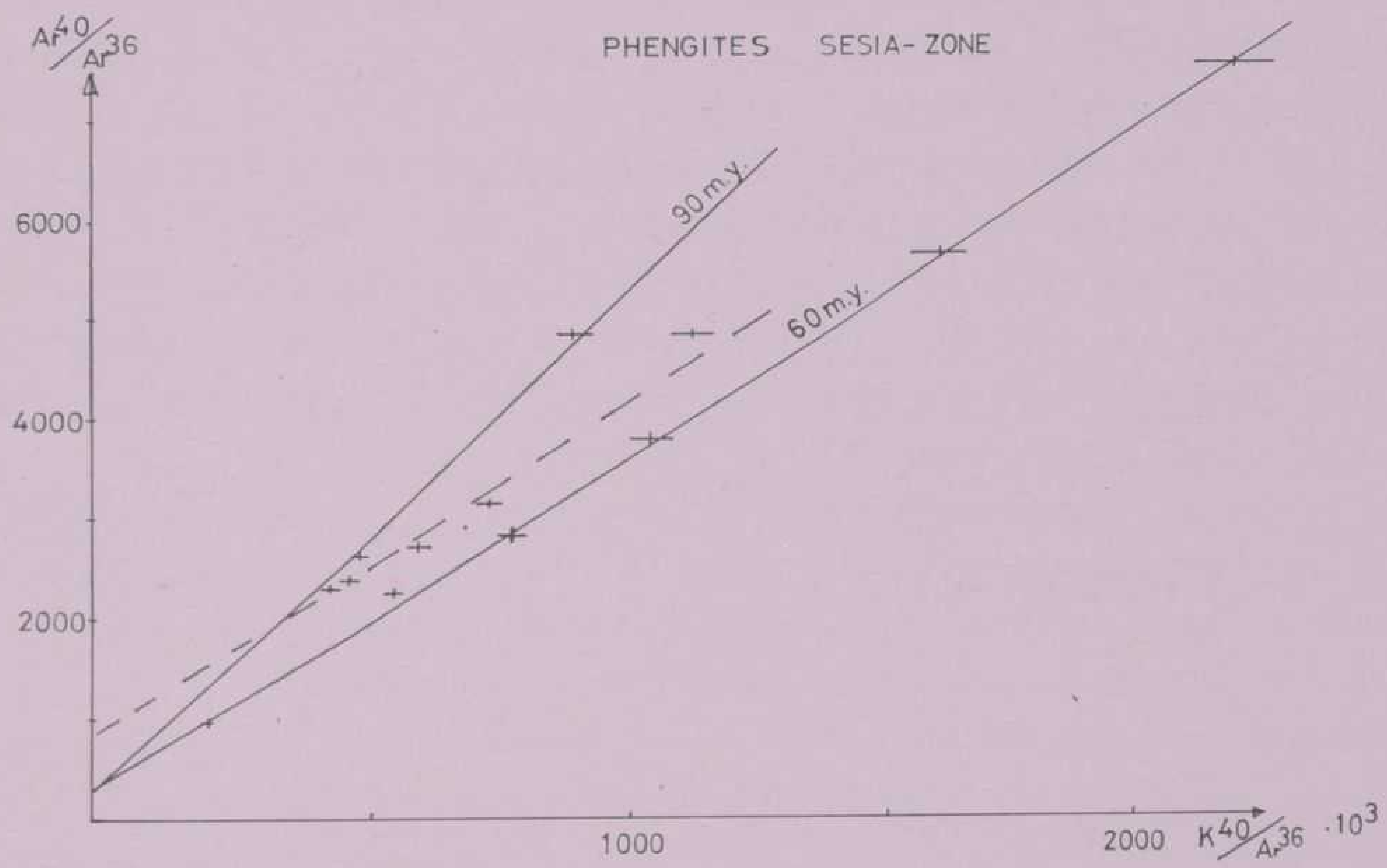

FIG. 8 - Ar^{40}/Ar^{36} versus K^{40}/Ar^{36} isochron plot of eo-Alpine phengitic micas of the Sesia-zone. The apparent ages range between 60 and 90 m.y.. If inherited argon is accepted all ages can be interpreted to be around 60 m.y..

paragonite was found. The eclogites of the Sesia-zone are composed of various rock types including garnet- and omphacite-bearing micaschists, eclogitic glaucophanitic micaschists, glaucophanitic eclogites and glaucophanitic amphibolites. In other words various combinations of the three principal componentis, garnet, omphacite and glaucophane and all transformations toward amphibolite are present (VITERBO-BASSANI and BLACKBURN (1968)). White micas are very abundant in all the eclogites. According to G.V. DAL PIAZ *et al.* (1972) the eclogitic high pressure mineral assemblage indicates higher pressures in the south west and lower pressure assemblages in the north east of the Sesia-zone. In the southwestern parts lawsonite, jadeitic pyroxene, glaucophane and phengite are found, towards the northeast first lawsonite then glaucophane and jadeitic pyroxene disappear and in the north eastern part of the zone only phengite is left from this mineral assemblage. The omphacite normally found contains around 50% - 80% of jadeite component but in some rocks of granitic composition nearly pure jadeite is found (VELDE and KIENAST, 1973).

Apart from the minerals already mentioned, minerals of the epidote group (zoisite, clinozoisite and Fe-Epidote), chloritoid, and kyanite are quite abundant. Quartz is always present, and in the eclogites rutile is the main titanium mineral.

The polyphase character of the high pressure metamorphism is evident from different generations of the same minerals. At least two garnets, two omphacites (besides chloromelanite), and different alkaliamphiboles ranging from glaucophane-crossite to blue green hornblende are found. Actinolite is very abundant and two generations of chloritoid have been described.

The Rb/Sr work involved in total rock systems in the Sesia-zone is not yet finished, but we can already draw some conclusions. Among the eclogitic rocks there are at least two different starting points for evolution. One rock type shows low $Sr^{87}/^{86}$ (below 0,710) and a second type shows $Sr^{87}/^{86}$ initial values of over 0,720. This information indicates that at least some of the eclogites were originally continental crustal material. On the basic of petrological evidence G. V. DAL PIAZ *et al.* (1972) came to the same conclusions. The Sesia-zone shows all transitions from biotite granite to rocks composed of jadeitic pyroxene, garnet, quartz, rutile and phengite. It is not yet known to what extent this transition is isochemical but it is clear that this eclogitic rock was originally a Hercynian granite and therefore has a higher $Sr^{87}/^{86}$ initial value than an eclogite originating in a basic rock that was derived from the Upper Mantle (e.g. former Ivrea basics or ultrabasics).

In section b), Canavese-zone, we have seen that the age of this eclogitic rock sequence was long thought to be Hercynian (A. BIANCHI and Gb. DAL PIAZ, 1963) but that according to SCHEURING *et al.* (1974) the last metamorphism must be of Alpine age. Age determinations on alkali-amphiboles and omphacites of the Sesia-zone present special problems, and are therefore discussed in section III 3 c. (anomalously high ages, a case of argon overpressure?). The few mica ages in the gneiss minuti seem to correspond to the mica ages of the Lepontine crystallization, giving ages up to 40 m.y. (Plates I and II and Tables 2 and 3). The phengites of the Micascisti Eclogitici give ages between 60 - 90 m.y. (Plate II and Fig. 8, Tables 2 and 3) suggesting an eo-Alpine phase of metamorphism in Upper-Cretaceous times. The 200 ± 20 m.y. old biotites of the Seconda Zona Diorito-Kinzigitica show a close relationship to the Ivrea-zone.

The Sesia-zone is separated from the Canavese and the Ivrea-zone by the Insubric-Line, a major fault system (AHRENDT, 1972 and in preparation) separating Alpine metamorphic rocks in the north from pre-Alpine metamorphism in the south (GANSSER, 1968).

d) Dent Blanche Nappe

The Dent Blanche Nappe system *s.l.* consists of Dent Blanche and Mont Mary Nappe with some associated Klippen on the Mesozoic (Mont Emilius, Rafray and Pillonet), G.V. DAL PIAZ and SACCHI (1969), G.V. DAL PIAZ and NERVO (1971), CARRARO *et al.* (1970), DAL PIAZ, GOSSO and MARTINOTTI (1971), DIEHL (1938), MASSON (1938), STUTZ (1938) (Figs. 1 and 16).

The Dent Blanche nappe system is composed of two nappes: The Arolla nappe and the discordantly overlaying Valpelline nappe. The Valpelline nappe forms a large syncline separated by a structural unconformity from the Arolla nappe below. The synclinal axis plunges about 5° to the southwest.

The Arolla series contains mainly acid plutonic rocks and their metamorphic derivatives: the Arolla gneisses, chlorite-albite gneisses and schists, and phengite-alkali feldspar gneisses. Amphibolites and gabbros are more rare. The above mentioned series is markedly acid in composition and resembles the Sesia gneisses - the only exception being that eclogites are missing from the Arolla series. The Valpelline series on the other hand is composed of garnet-biotite-sillimanite-alkali feldspar-gneisses and schists containing marbles and calc-silicate inclusions. Basic plutonites and amphibolites are widespread. This series is very similar to the Ivrea zone. Copper and Manganese ores are found in both and graphite is very common even in pegmatites.

Age measurements on micas from the Valpelline Series confirm the similarity between Valpelline and Ivrea rocks (Plates I and II, Table 1). Biotite and muscovite ages range between 180 and 200 m.y.. This range of ages is typical for Ivrea zone rocks, and it may be assumed that during the early Mesozoic, rocks of the Valpelline series, Seconda Zona Diorito-Kinzigitica, and the Ivrea zone were still lying together south of the Insubric line, slowly uplifting and cooling. These data provide an upper limit for horizontal movements in this part of the Alpine chain. No age measurements have so far been made in the Arolla series, but according to the distribution of Alpine metamorphic minerals (von Raumer, 1971, Fig. 6 and Niggli and Niggli, 1965, Fig. 1), the series is also thought to be affected by Alpine metamorphism.

2) The Pennine Domain

In the deeper Pennine nappes (the central Lepontine region of Wenk (1956)) the time of Alpine amphibolite facies metamorphism has been determined by the presence of the first Alpine metamorphic pebbles in the lower Oligocene conglomerates of the Molasse basin and the Western Alps (Ellenberger, 1952, Fuechtbauer, 1964, De Graciansky *et al.*, 1971). This is in good agreement with the geochronological evidence of Jäger (1970), and Hunziker (1970), wich gives ages between 36 and 40 m.y..

In the Western Alps Lemoine (1972) on the basis of stratigraphical criteria has identified an Upper Cretaceous phase of tectonics, the Devoluy phase with east west axes and later Oligocene and Miocene phases of tectonics with fold axes parallel to the Alpine arch. Grandjacquet and Haccard (1972) and Grandjacquet *et al.* (1972) and Haccard *et al.* (1972) have shown an important Albian phase, a late Eocene phase and a Miocene phase of tectonics in the Western Alps.

Van der Plas (1959), Niggli (1960) and Bearth (1959 + 1967) have described several phases of Alpine metamorphism in the Pennine region of the Central and Western Alps. Bearth (1967) identified four phases in the Pennine ophiolites where age relationships are very clear as pre-Alpine metamorphism is absent. Following the primary magmatic mineral assemblage, he finds jadeite or jadeitic pyroxene, rutile and garnet as a first high pressure low temperature metamorphic assemblage, and glaucophane, chloritoid, paragonite and talc as a second generation. The third and final metamorphic assemblage contains no jadeite or jadeitic pyroxene, but albite,

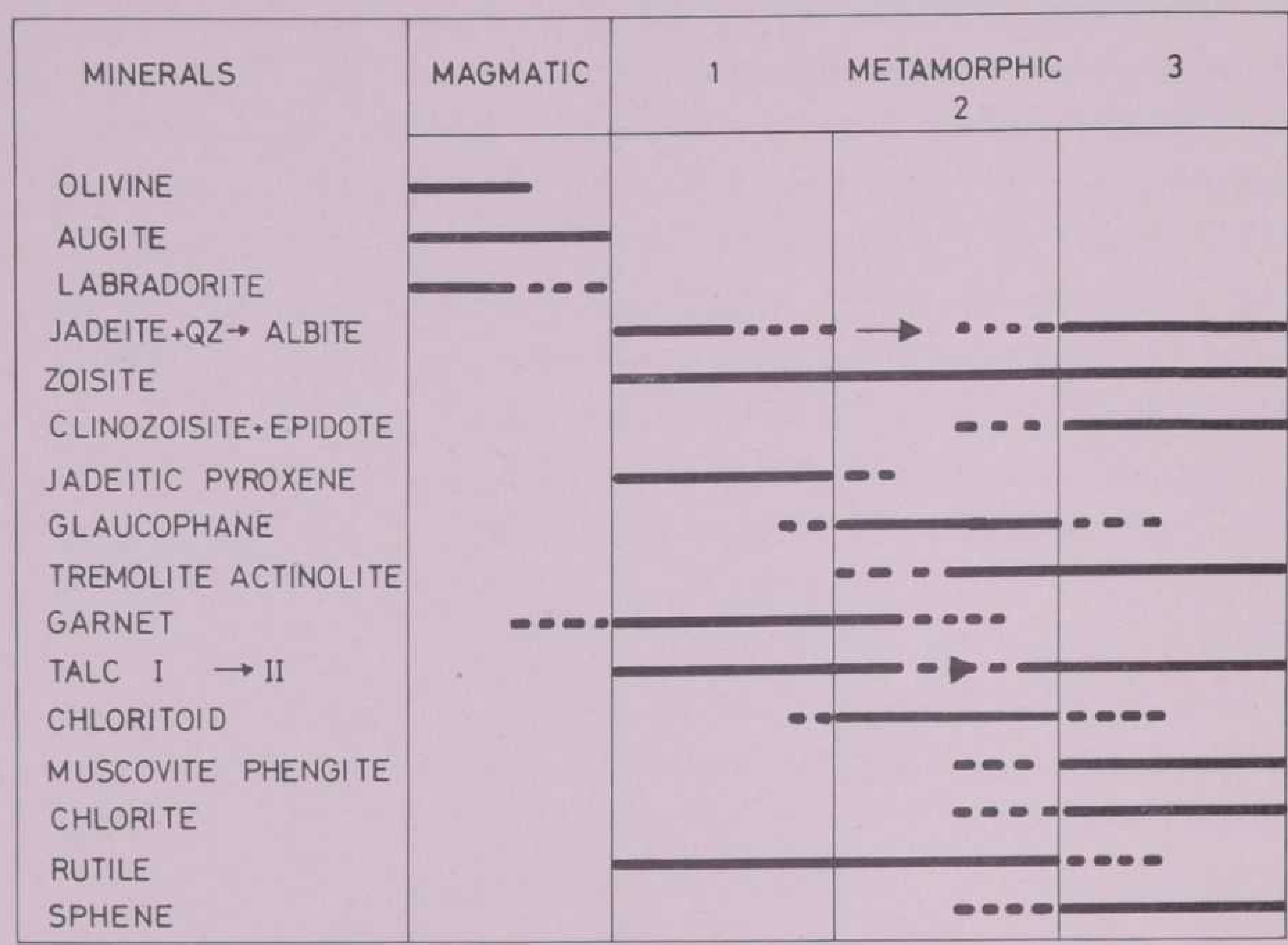

FIG. 9a - Correlation of magmatic and metamorphic mineral paragenesis in the Allalin gabbro according to BEARTH (1966), generalized for the metamorphosed Mesozoic ophiolites of the Pennine area. 1. High pressure low temperature eo-Alpine phase. 2. Transition. 3. Intermediate temperature and pressure Lepontic phase.

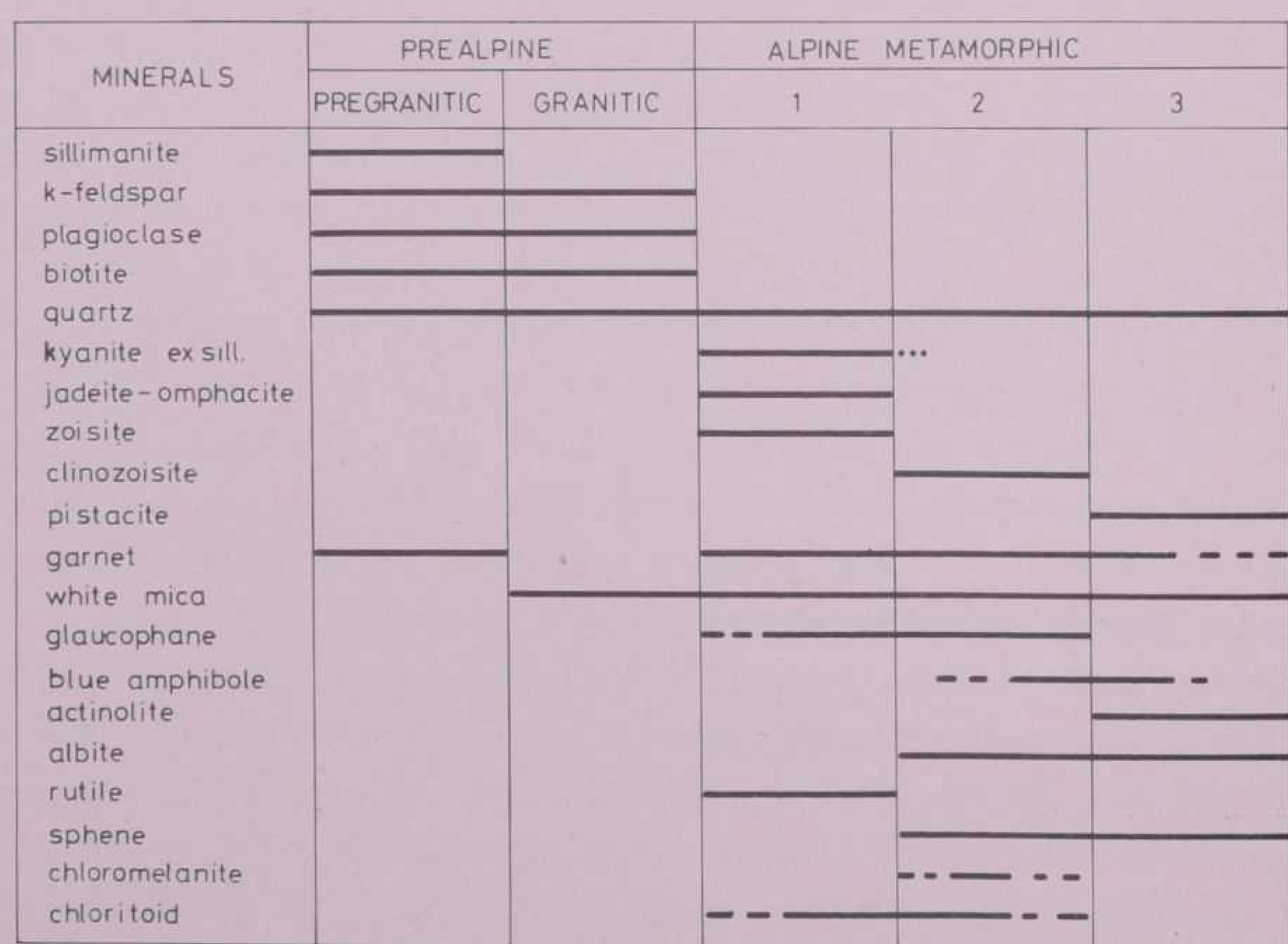

FIG. 9b - Correlation of metamorphic minerals in the Sesia zone according to DAL PIAZ *et al.* (1972+1973): Overprinting Herzynian and older remnants. 1) High pressure low temperature eo-Alpine phase. 2) Transition. 3) Intermediate temperature and pressure Lepontic phase paragonite, phengite and chlorite are common. Instead of rutile, the titanium mineral is sphene (Fig. 9a). The problem of determining the absolute age of these generations remains to be solved.

Pustaszeri (1969) gives K-Ar ages between 100 and 140 m.y. for a syenite of the Mont Genevre ophiolites in the Western Alps. Dietrich (1969) gives a K-Ar age of 113±4 m.y. for a magmatic hornblende from a diabase sill in the upper Pennine Platta nappe ophiolites.

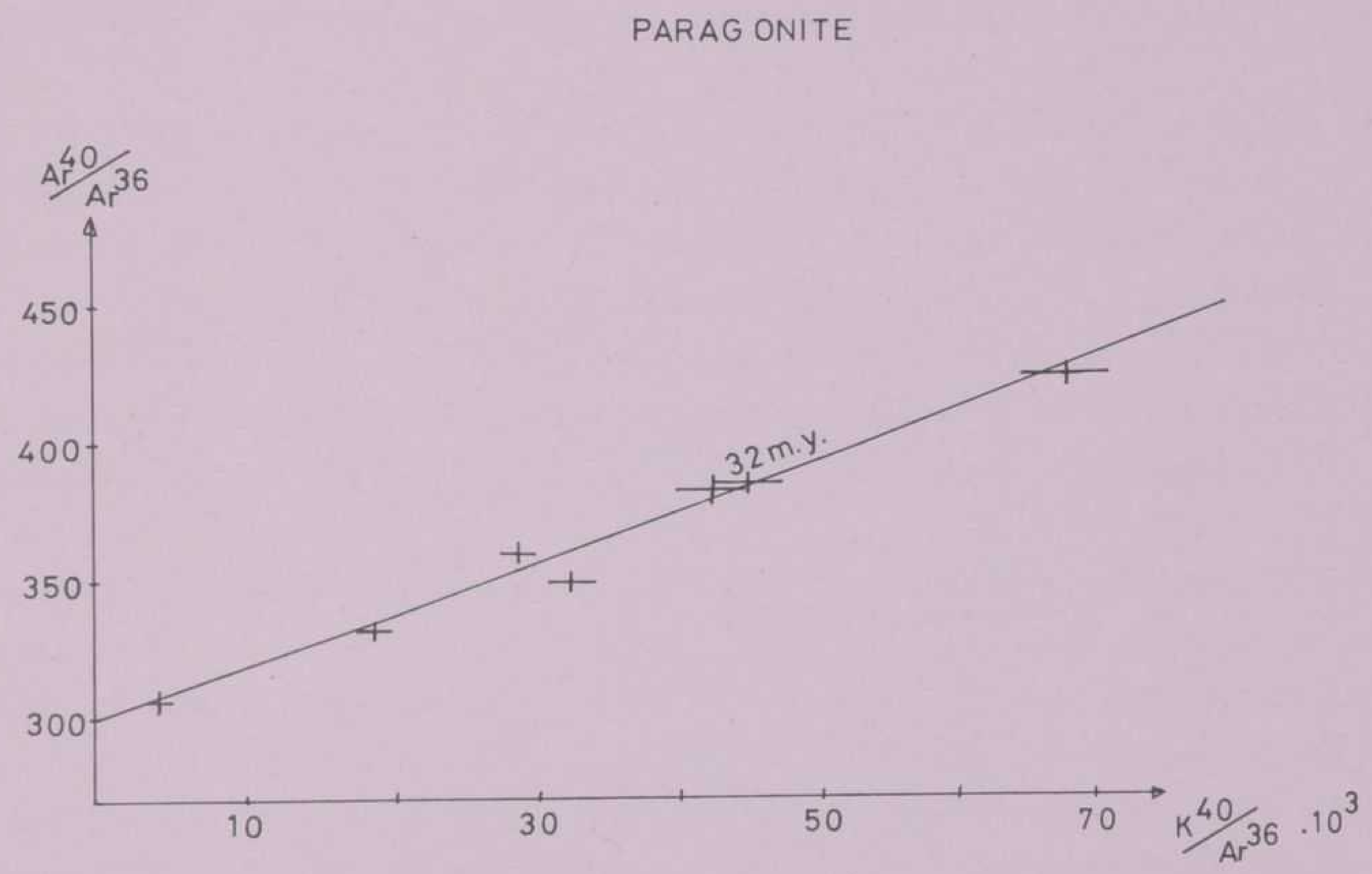

Fig. 10 - Ar^{40}/Ar^{36} versus K^{40}/Ar^{36} isochron plot of Lepontic paragonite. An older phase of paragonite formation is suspected but was not yet found.

Bertrand (1971) gives 11 ages between 140 and 180 m.y. for the Pennine ophiolites of the region of Gets in the Western Alps. Two samples with lower ages are discarded because of alteration. These ages all lie in the range between 100 and 180 m.y. or between middle Jurassic to middle Cretaceous with a climax in the upper Jurassic around 140 m.y. and correspond well with the fission track ages on zircons from the ophiolites of the Apennines 165 m.y. reported by Bigazzi *et al.* (1972). On geological grounds there is no argument against this time span for the intrusion of the ophiolites. The geological time mark for the Lepontine metamorphic phase is given by the lower Oligocene pebbles of metamorphic rocks in the Molasse so that 38 m.y. would represent the crystallisation age of the Lepontine mineral assemblages. The paragonite K-Ar ages of 32 m.y. (Fig. 10) fall into this phase. Between intrusion age and age of the Lepontine crystallisation there is a period of at least 100 m.y. during which the above mentioned high pressure metamorphism could have occurred. The same high pressure metamorphism we already found in the Sesia-zone (Fig. 9b). That Sesia- and Pennine-zone underwent the same high pressure metamorphism can best be seen on a map of the western Alps with the distribution of some critical minerals and rocks according to BEARTH (1962), BOCQUET (1971) and personal communication, BORTOLAMI and DAL PIAZ (1970), GAY (1970 and 1972), GUITARD and SALIOT (1971), LORENZONI (1965), MARTINI and VUAGNAT (1970), NIGGLI (1970), NIGGLI and NIGGLI (1965), SAWATZKI and VUAGNAT (1971), SALIOT (1973), WENK (1962). The external zone is characterized by a weak metamorphism in the Laumontite-Pumpellyite-Prehnite facies. In the Piemont region alkaliamphiboles (glaucophane to crossite) are found, lawsonite with jadeite in the SW and omphacite in the north east. Eclogites are also very common (see Fig. 11). The high pressure mineral fields cross tectonic boundaries and must therefore by younger than the present tectonic pattern.

On the other hand the high pressure mineral field is cut by the region of Lepontine crystallisation and must therefore be older than 40 m.y.. It seems plausible to correlate the high pressure metamorphism with the upper-Cretaceous phase of tectonics described by LEMOINE and by GRANDJACQUET *et al.*. The correlation is supported by the fact that in the Piemont basin no Upper-Cretaceous sedimentation has so far been found. In the Briançonnais domain, where the sedimentation goes as far up as the Paleogene (in some cases Eocene has been proved) jadeite (Fig. 11) is found.

This presents the problem that either the Tertiary in the Briançonnais is allochthonous or two successive phases of high pressure low temperature metamorphism must be postulated. RAMSAY (1963) mentions the wide distribution and intensity of the pre-Eocene erosion in parts of the sub-Briançonnais zone and the internal Dauphinois zone, which suggests that at least sedimentation was not continuous at that time. K-Ar ages on alkaliamphiboles of the Pennine region are a valuable tool for solving this problem. The oldest alkaliamphiboles (glaucophanes, crossites, and blue-green amphiboles gave ages of 80-100 m.y. (Fig. 12 and Table 3) which are in good agreement with the 60-90 m.y. old phengites found in the Sesia-zone. The upper Cretaceous alkaliamphibole ages were restricted to the Piemont basin (Fig. 2). Younger alkaliamphibole ages around 40 m.y. and 20 m.y. (Fig. 13 and 14 and Table 3) were also found. These younger amphibole ages have a wide distribution also in the Briançonnais (BOCQUET *et al.*, 1973).

Besides the age difference alkali-amphiboles show other differences: 80-100 m.y. old glaucophanes are mostly randomly oriented and occur only in the Piemont region. According to BOCQUET (1973) the chemistry of these glaucophanes varies from glaucophane-ferroglaucophane to crossite. The younger alkaliamphiboles (40-50 m.y. and 15-30 m.y.) occur partly in the Piemont partly in the Briançonnais domain, where, also according to BOCQUET (1973), riebeckite and magnesio-riebeckite besides glaucophane-crossite are found. These younger amphiboles show mostly a strong orientation parallel to the dominant B-axes. CHADWICK (1973), on structural criteria, showed in the Monte Rosa-nappe that these amphiboles must be younger than the main nappe formation, as they are cogenetic with the late Alpine Mischabel back fold. Therefore, it can be concluded that either glaucophane formed at different times or the early glaucophane has been rotated into the direction of later fold axes, thereby loosing its

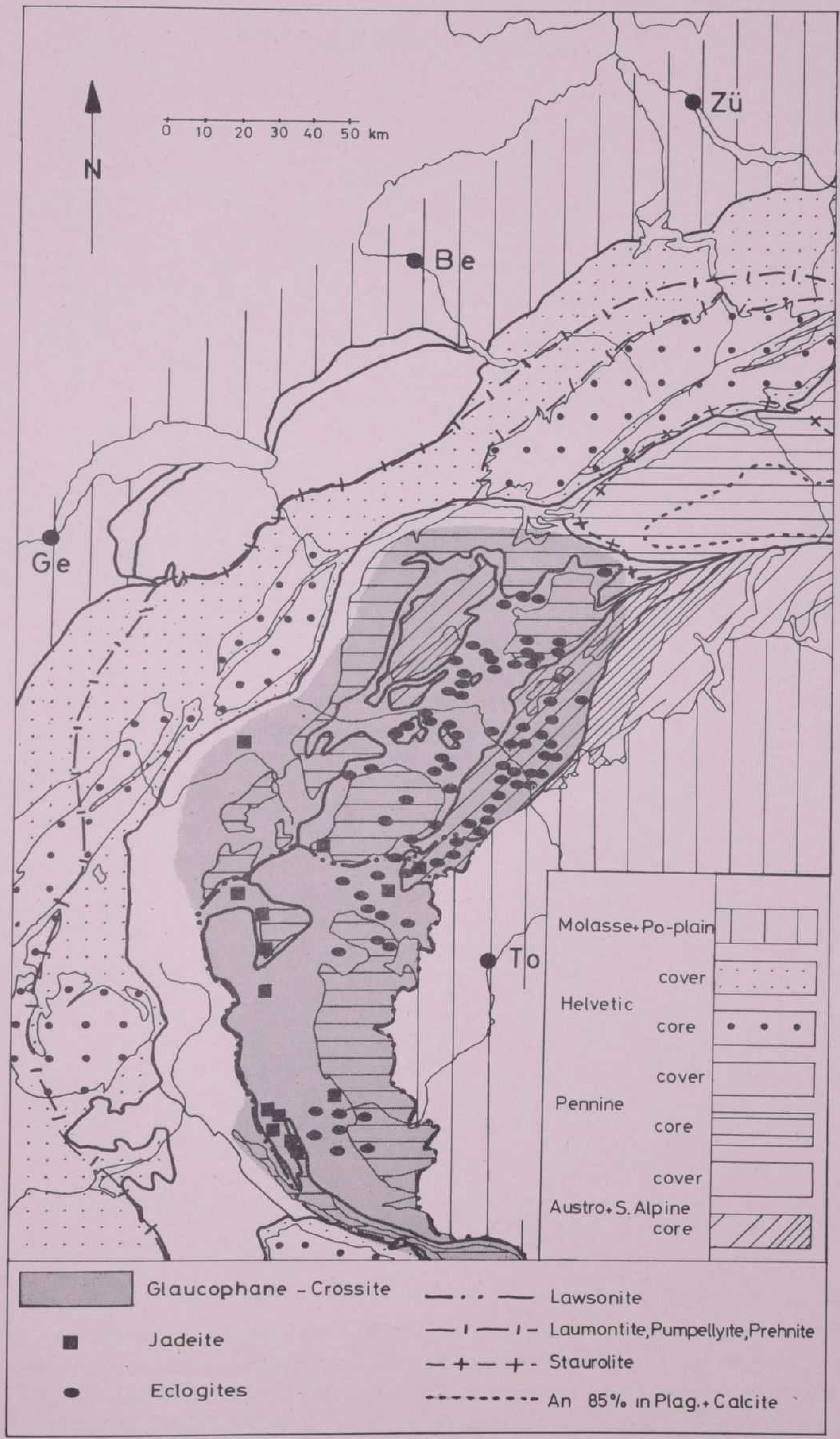

Fig. 11 - Tectonic sketch map of the central and western Alps (as. Fig. 1) with the distribution of eclogites, jadeite, glaucophane-crossite, lawsonite, laumontite-pumpellyite-prehnite, staurolite and An 85% in plagioclase + calcite. The high pressure mineral field crosses the tectonic boundaries and must therefore be younger than the present tectonic pattern. On the other hand the high pressure mineral field is cut by the region of Lepontine cristallisation and must therefore be older than the Lepontine phase.

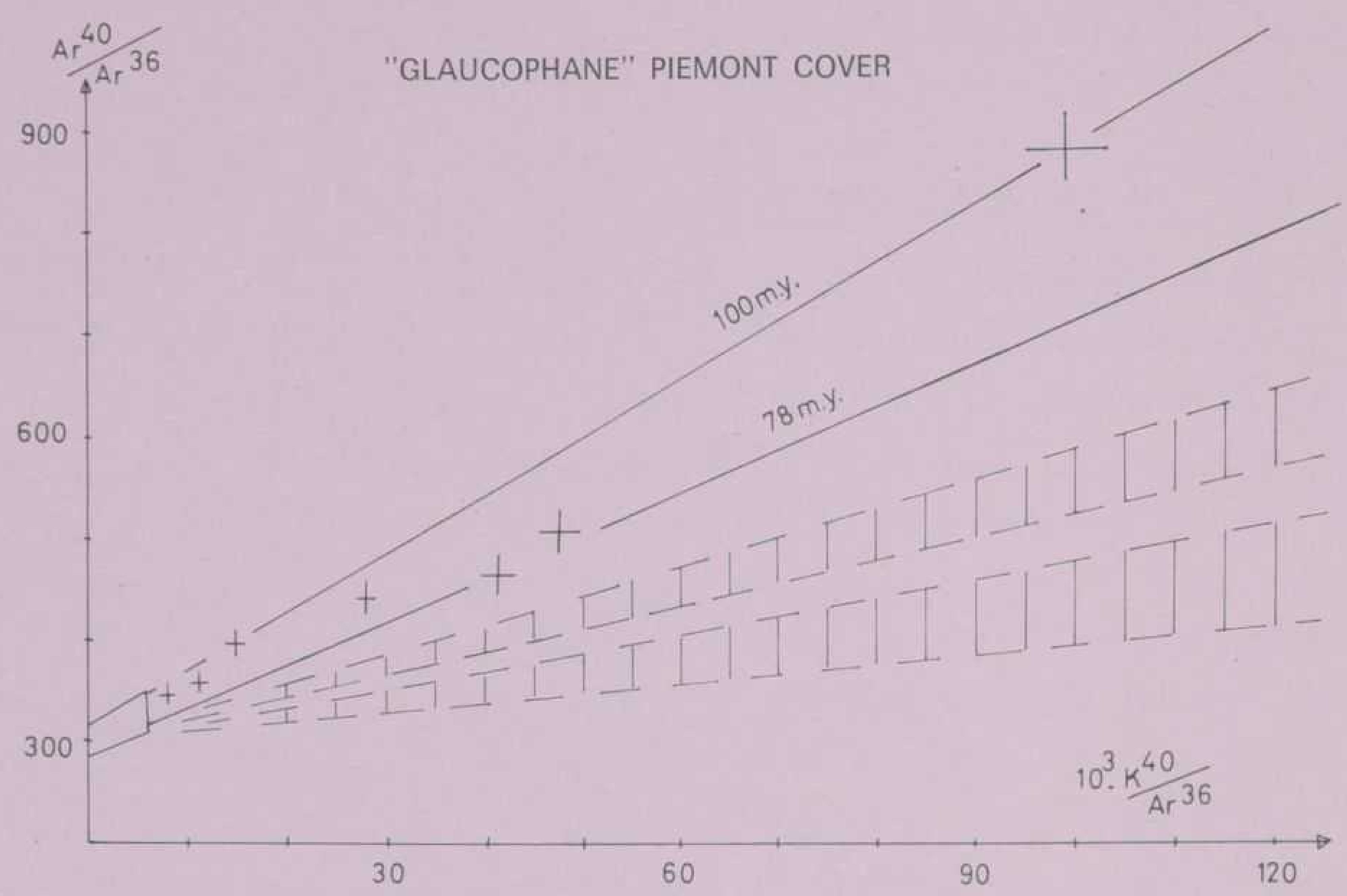

FIG. 12 - Ar^{40}/Ar^{36} versus K^{40}/Ar^{36} isochron plot of glaucophanes - crossites and blue green amphiboles of the Piemont basin ophiolites giving an apparent age of about 90 m.y.. The normal initial values of Ar^{40} / Ar^{36} and the initial Ar^{40}/Ar^{36} of cogenetic potassium poor to potassium free minerals of 298 ± 7 led to the interpretation of 80-100 m.y. as true age.

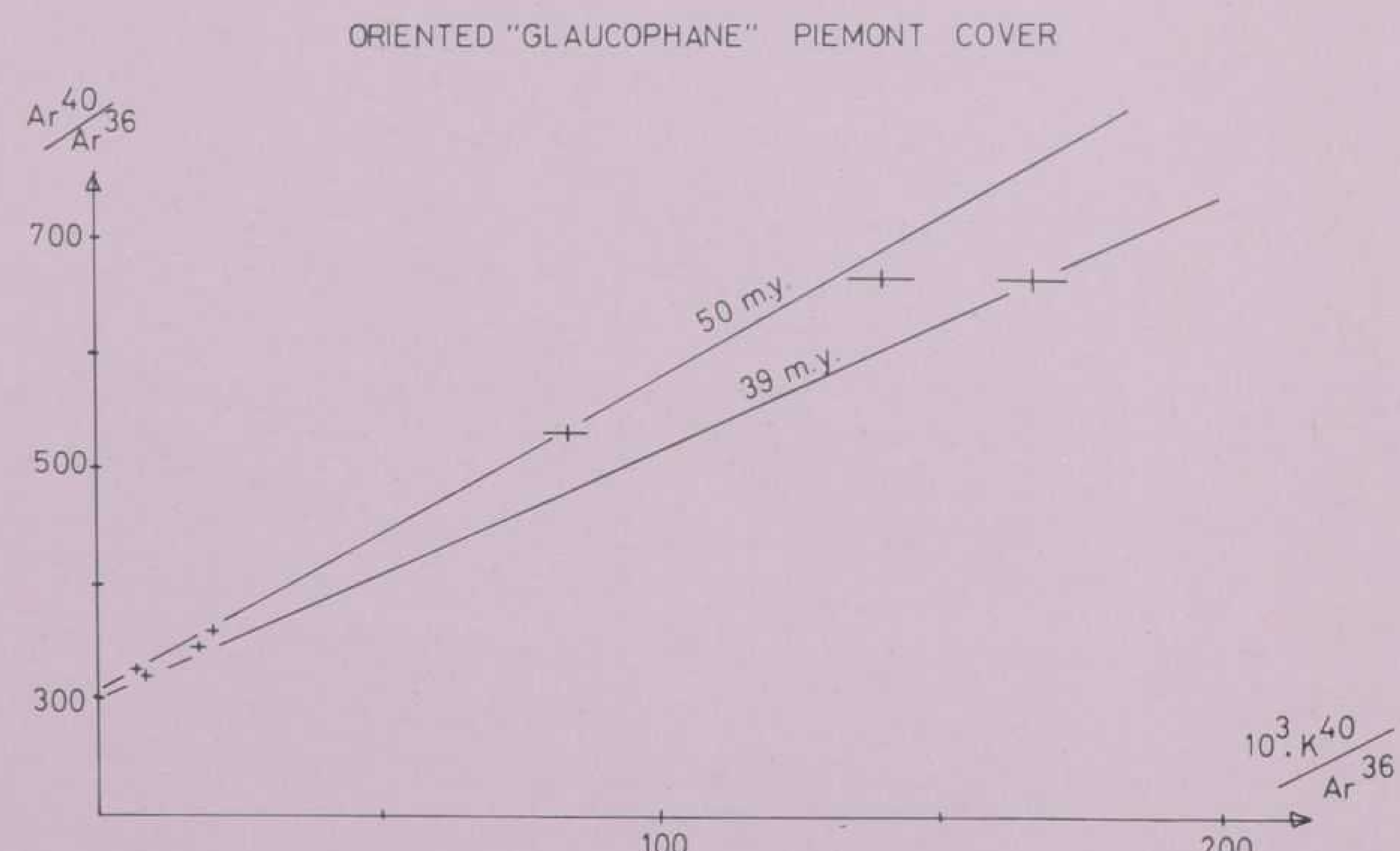

FIG. 13 - Ar^{40}/Ar^{36} versus K^{40}/Ar^{36} isochron plot of glaucophanes, crossites and blue green amphiboles of the Piemont basin ophiolites giving an age of about 40 m.y..

argon. This seems also a plausible explanation for the fact that SUPPE and ARMSTRONG (1971) and COLEMAN and LANPHERE (1971) report lower ages for glaucophane than for cogenetic phengite in the Franciscan. The geological interpretation does not change, whichever model is accepted. The oriented glaucophanes from the Zermatt-region with Miocene ages most likely indicate the time of the back folding.

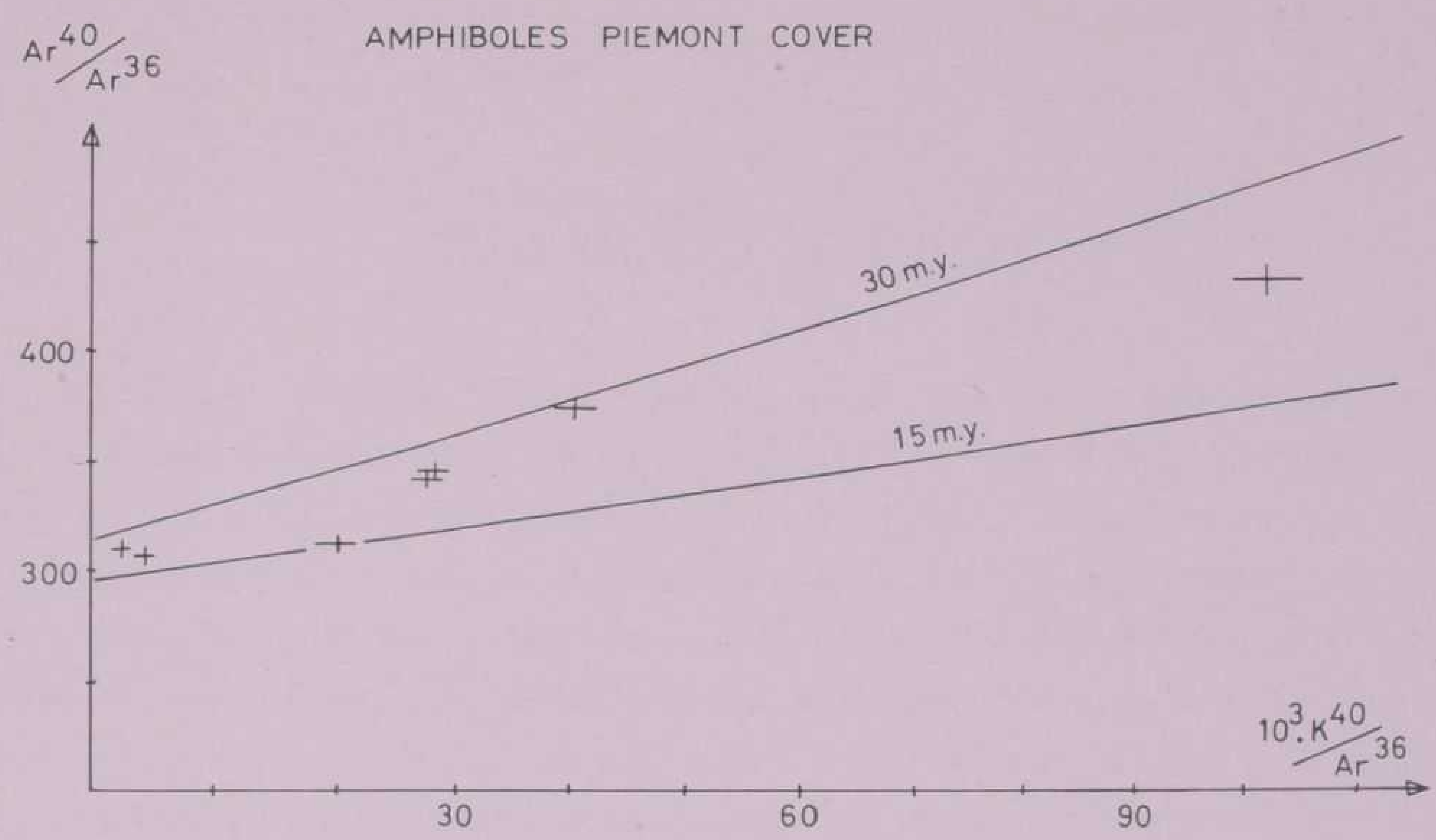

FIG. 14 - Ar^{40}/Ar^{36} versus K^{40}/Ar^{36} isochron plot of amphiboles (glaucophane, crossite, riebeckite, blue green and green amphibole of the Piemont basin ophiolites giving an age of around 20 m.y.. In contrast to the eo-Alpine alkaliamphiboles the 20 m.y. amphiboles are mostly strongly oriented.

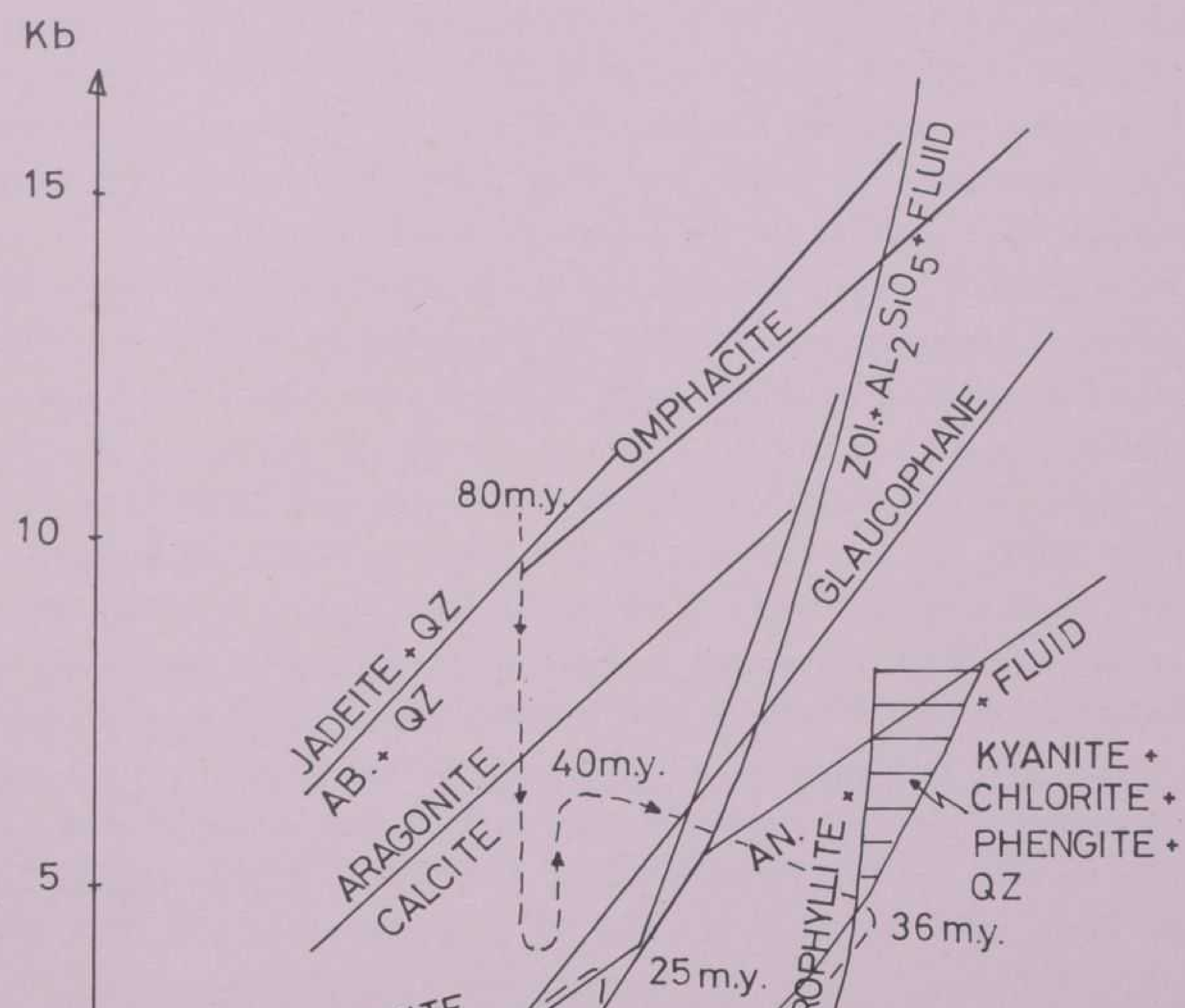

FIG. 15 - Schematic representation of the P-T conditions during the plurifacial metamorphism in the region between Simplon pass and the Aosta valley.

V. GEOLOGICAL CONSEQUENCES

According to Crawford and Fyfe (1965), Ernst (1963), Johannes *et al.* (1971), Johannes and Puhan (1971), Liou (1971), Newton and Kennedy (1963, 1968), Newton and Smith (1967), Nitsch (1972), Velde (1965), Velde and Kornprobst (1969) and Fig. 15, pressures between 8 and 12 kb and temperatures between 200 and 400°C must be taken into consideration for the early high pressure mineral association. This would represent an overburden of 30 - 45 km of which in some places only 15 km can be found today. In other places there is no evidence for an overburden greater than about 5 km. This would mean that in order to explain the high pressure as tectonic or fluid overpressure according to De Roever (1970 and 1972) the unlikely amount of about 6 kb of overpressure would be required. On the other hand the implicitly low thermal gradient of 5 - 15°/km instead of around 30°/km postulated for the Lepontine metamorphic phase of the central Alps by Clark and Jäger (1969) requires a mechanism other than simply piling nappes on top of each other in a geosyncline. The resulting pile of slowly warming nappes would destroy the low temperature-high pressure mineral association and a high-temperature-medium pressure assemblage like in the Lepontine would develop.

The steep gradient for pressure and the low gradient for temperature during the eo-Alpine phase of metamorphism as well as the parallel trend of eo-Alpine and later (Lepontine and Miocene) metamorphic belts in the western Alps show certain similarities with the Sambagava belt and the Canto mountains of Japan or the Franciscan terrain of western California (Banno, 1958), (Coleman and Lanphere, 1971), Coleman (1966, 1971), Coleman *et al.* (1965), Ernst (1971), Miyashiro (1961, 1967), Seki and Takizawa (1965), Yamaguchi and Yanagi (1970). By analogy, a plate tectonics model can be applied to explain the setting of this early phase of Alpine metamorphism in the Western Alps as has been suggested by previous workers.

Two models have been suggested to explain the tectonic setting of the western Alps. The plate tectonics model and the more complex flake tectonics model.

a) *Plate tectonics model* (Oxburgh and Turcotte, 1968, Hunziker, 1970, Dewey and Bird, 1970, Ernst, 1971 and 1973, Hunziker, 1971, Dal Piaz *et al.*, 1972, Saliot, 1972).

According to this model the Piemont basin and parts of the Sesia-crystalline, as well as the southern parts of the Pennine basement nappes, descended with a subducting northern lithospheric slab along one or several trenches (Fig. 16). The pressure increased simultaneously with the downward movement. The temperature increase was minimal because of the downward-moving cold, wet and unconsolidated sediments in the basin and because of the low heat conductivity in rocks. This accounts for the low thermal gradient.

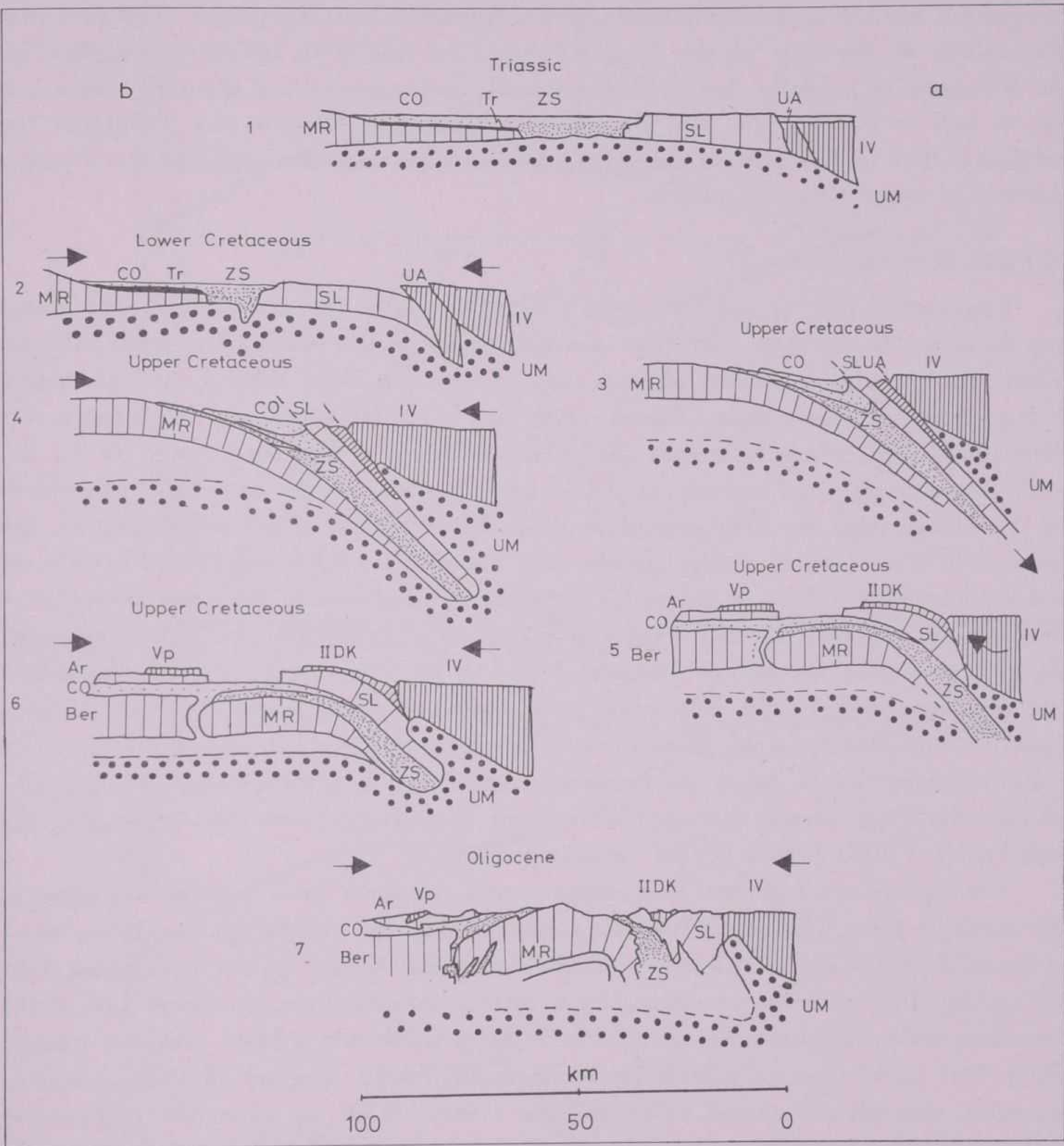

Fig. 16 - Schematic profiles showing the tectonic evolution of the North Occidental Alps. a) Flake tectonics model. b) Plate tectonics model.

Legend: IV = Ivrea-Verbano-zone. S.L. = Sesia-Lanzo-zone. UA = Upper Austroalpine comprising II DK Seconda zona diorito-kinzigitica (Klippen of the Ivrea-Valpelline system) and VP Valpelline nappe. AR = Arolla nappe. MR = Monte Rosa nappe. Ber = Bernhard nappe. ZS = Zermatt-Saas-zone. Co = Combin-zone. UM = Upper Mantle.

Assuming rates of movement of 2 cm per year dephts of 40 km are attained in 4 m.y. of subduction along the Benioff zone at an angle of 45°. 2 cm per year is a slow movement according to Oxburgh and Turcotte (1968). They calculated their model assuming a rate of 5 cm per year. This downward movement must have stopped and upward movement began at some point in time, otherwise the temperature would have risen to the normal value at that depth, changing the mineral assemblage. To warm these rocks up would have taken at least 20 to 30 m.y. according to Oxburgh and Turcotte (1971) — the time span between the high pressure metamorphism and the high temperature Lepontic phase of metamorphism. The fact that glaucophane at the base of the Ivrea-Klippen (Seconda Zona Diorito-Kinzigitica) on the Sesia-zone is partially destroyed mecanically and recrystallized through overthrusting, as well as the fact that the phengites yield ages of 60 - 90 m.y., leads to the conclusion that in this part of the Alps, Austroalpine nappes overthrust the Pennine elements in upper Cretaceous times.

b) Flake tectonics model

LAUBSCHER (1971) and OXBURGH (1972) brought the flake tectonics model into discussion in the Alps. The Alps are interpreted as the result of a continent/continent collision with a sheared off top part of one continent driven over the other as large basement thrust sheet (Flake). OXBURGH (1972) comes to this picture for the Eastern Alps, where he argues that plate thickness is only between 4 to 12 km while the common plate tectonics model is dealing with plates 60 - 100 km thick. In the western Alps the European plate (Pennine zone) has a normal thickness, but the African plate (southern Alps) shows only about 5 km thickness in the Ivrea-zone, and is more likely a flake in Oxburgh's terminology. Following this interpretation a sheet can be hypothesized that scrapes offocean floor sediments and ophilites along the way, generating the tectonic melange found in the Piemont at present (ophiolites and Bündner-schiefer). The front-most part of the overriding basement thrust sheet is found as Dent-Blanche-nappe more than 60 km from the original plate boundary. The wedge of Upper mantle below the Ivrea-zone could then be interpretated as being split off from the Upper mantle through the northern continental plate thus generating the well known « birds head » of the seismic profiles.

The high pressure mineral assemblage would originate in a subduction zone at the northern plate boundary (Pennine zone). During the continental collision some of the subducted material is scraped off the continental border by the overriding flake and emplaced in its present position. As a further complication, the front part of the overriding flake (Sesia-zone) must also have been subducted (high pressure paragenesis). This model gives us a plausible explanation for the reversal of the subdutcion movement through continental collision. This reversal finds no plausible explanation in ERNST's plate tectonics model. Thus subducted material gets dragged back to surface by the overriding flake of the southern plate.

In trying to fit the data from this paper to this model the following picture is obtained.

1) After the Hercynian metamorphism in the upper Carboniferous, elevation of the Strona-Ceneri zone occured along the Pogallo line, a side branch of the Insubric line separating Strona-Ceneri from the Ivrea-Verbano zone (BORIANI, 1970). During Mesozoic and early Tertiary the Ivrea and Strona Blocks were both lifted to their present position (cooling down of the Ivrea block to 300°C during Jurassic) ([1]).

[1] (Since Oligocene this relation has changed and the pronounced uplift is noticed in the Alpine metamorphic block north of the Insubric line. The Oligocene Biella and Traversella plutons (KRUMMENACHER and EVERDEN, 1960 and HUNZIKER and BEARTH, 1969) north of the Insubric Line today lie on the same level with the Oligocene andesites. As already mentioned a displacement of at least 4 km must be assumed along the Insubric Line since the Oligocene. An analogous uplift of the northern block was reported by HUNZIKER (1970) along the Simplon Centovalli line, a northern branch of the Insubric line).

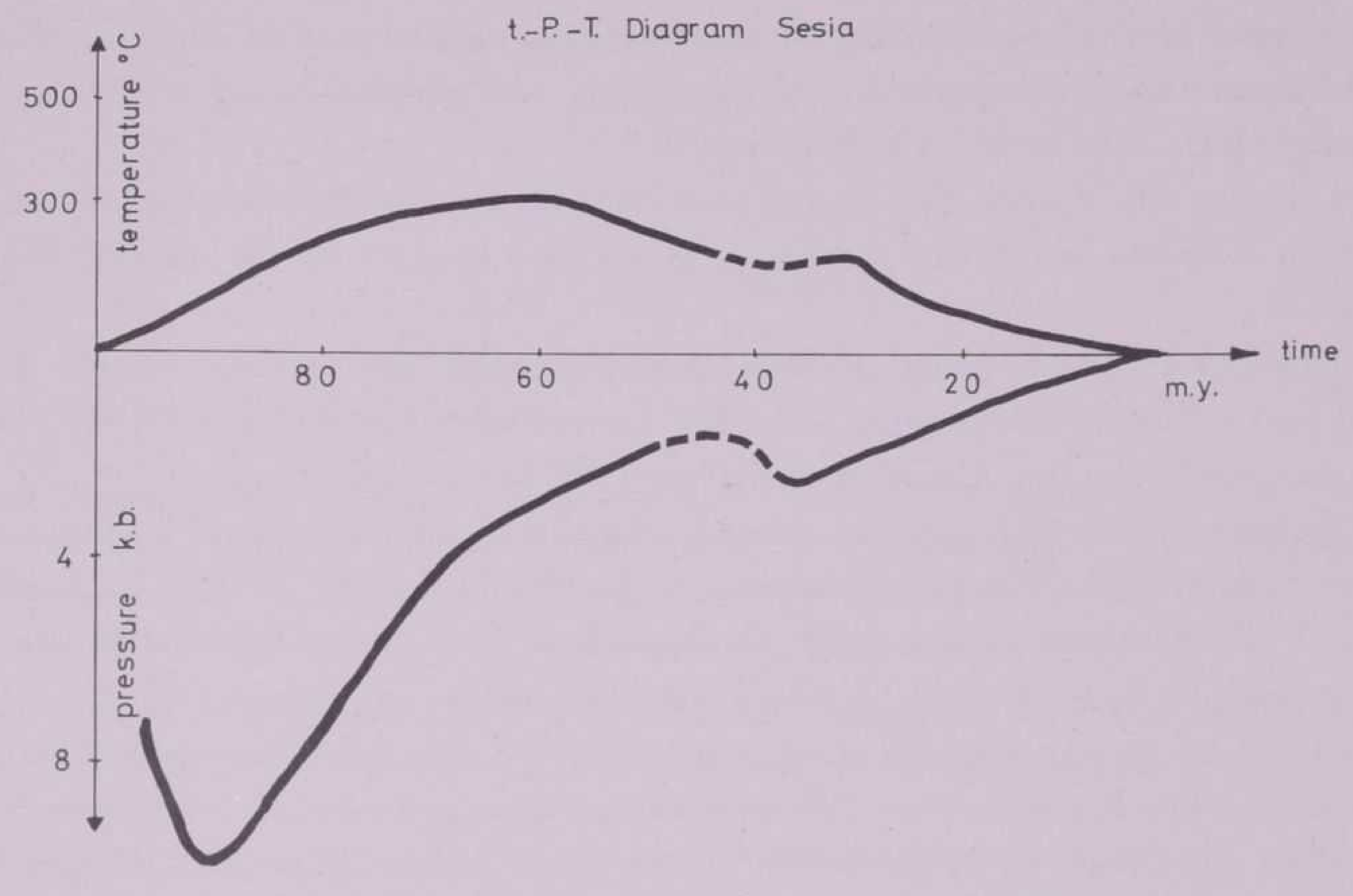

FIG. 17 - Time pressure temperature diagram for the Sesia zone during the different phases of Alpine metamorphism as deduced from geochronological and petrological data.

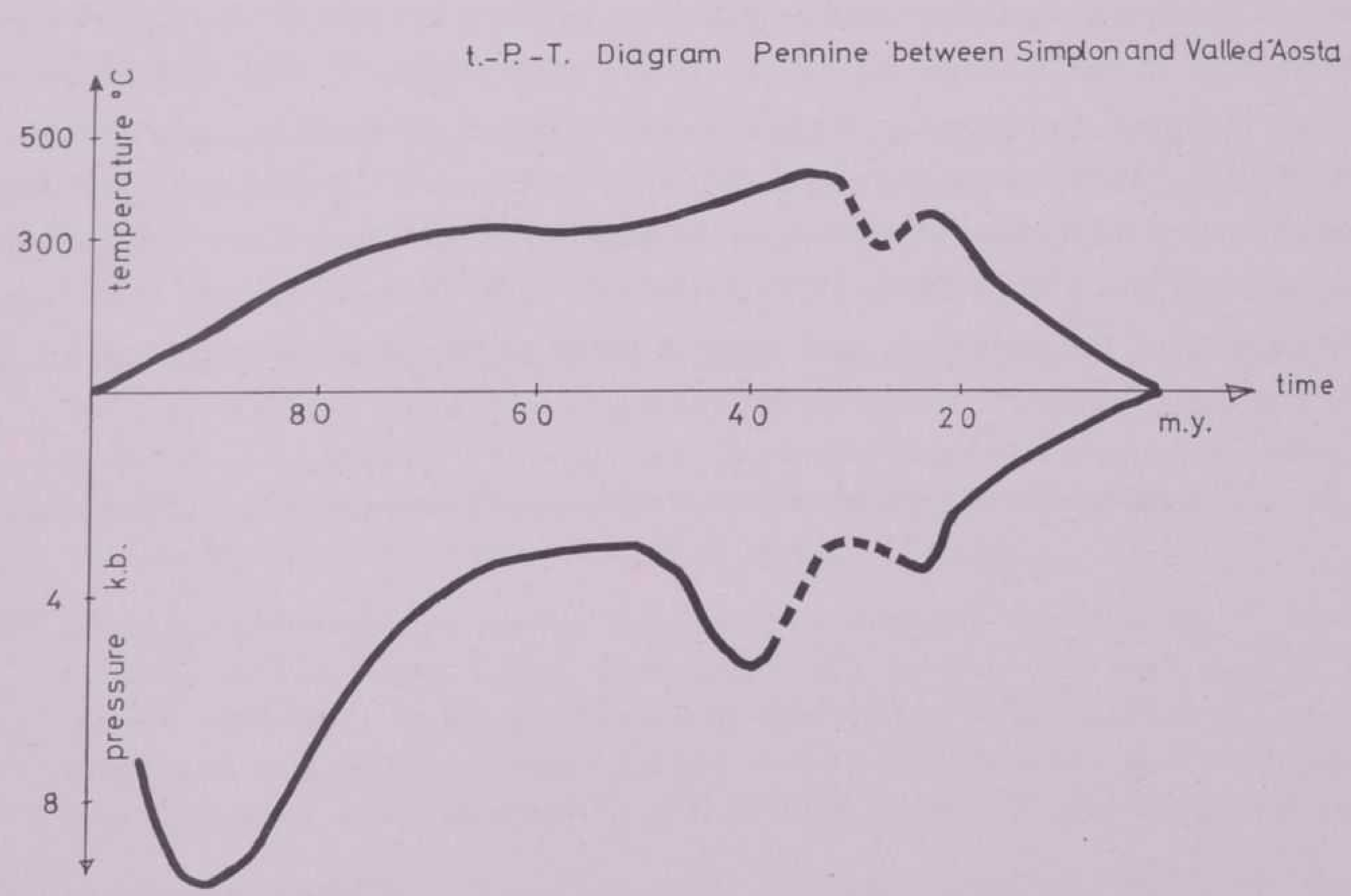

FIG. 18 - Time pressure temperature diagram for the Pennine zone between Simplon and Vale d'Aosta during the different phases of Alpine metamorphism.

The 120 m.y. Rb-Sr whole rock isochrons found in the front part of the Pennine nappes by HANSON *et al.* (1969), HUNZIKER (1970) and JÄGER, HUNZIKER, GRAESER (1969) together with the isotope data of the ophiolites (100-180 m.y.) seem to mark the beginning of the horizontal movements. In any case, the upper Cretaceous flysch sedimentation must have resulted from earlier movements. These may well have started in lower Cretaceous or Jurassic time, as a consequence of ocean floor spreading together with the intrusion of the ophiolite masses.

2) Upper Cretaceous thrusting of Austroalpine elements over Pennine elements and of Piemont basin sediments over Briançonnais and generation of a very complex schistosity (DAL PIAZ *et al.*, 1972) occurred.

3) During the Eocene the Briançonnais was thrust over Helvetic rocks and E - W folds with a second schistosity according to GRANDJACQUET *et al.* (1972) were generated.

4) During a Miocene phase Helvetic units overthrust the Molasse basin, and the general backfolding was developped. The EW lineament of LAUBSCHER (1970) and the fold axes parallel to the Alpine Arch (CABY, 1973) were generated.

The temperature time pressure diagram for the Sesia-zone Fig. 17 shows a first pressure peak around 90 m.y. in analogy to the Pennine units of the Western Alps (Fig. 18), and a second pressure peak in connection with the generation of the subsequent greenschist facies Eocene/Oligocene metamorphism and schistosity. The temperature builds up slowly reaching a climax around 60 m.y. (cooling ages of the Sesia-phengites). In the Pennine domain the second pressure peak around 40 m.y. is more pronounced. This leads to the generation of the dominant foliation and the third Miocene peak is only of minor importance. In the Pennine the temperature builds up to a maximum at around 40 m.y. showing togother with the data of FRY and FYFE (1971) that during the eo-Alpine phase of metamorphism the energy transport through fluid phases also in the western Alps is of minor importance. A fast energy transport would have destroyed the primary high pressure mineral assemblage completely and the time difference between pressure and temperature increase would have to be smaller.

Therefore the main part of the water of the sediments must have left before this Alpine metamorphism - most likely during the 120 m.y. tectonic phase, thus resetting the Rb-Sr system of the sediments and even of some of the gneisses involved.

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VI. APPENDIX

1) Sample, Location and Description

KAW 80 Granodiorite, Ivrea-zone, little quarry at Camponi, Toce. Coord. 676,400/89,500. 200 m a.s.l. The rock contains plagioclase, biotite, quartz, garnet. Zircon and opaque minerals at the rims of biotite are minor minerals. The plagioclase is mostly fresh, in parts a little sericitized. Macroscopically a fine grained granitoid rock.

KAW 81 Phlogopite peridotite, Ivrea-zone, E. Finero, along road Finero-Cannobbio. Coord. 685,690/106,600. 830 m a.s.l. The rock consists of olivine and phlogopite. Minor minerals are clinopyroxene, pargasitic hornblende and spinel. The subparallel orientation of the phlogopite gives the rock a parallel texture, whereas the phlogopite-free peridotite has a more massive texture.

KAW 85 Alkalifeldspar-garnet-sillimanite gneiss, Ivrea-zone, old fortification of Teglia, Toce. Coord. 674,500/93,000. 210 m a.s.l. The rock contains quartz, plagioclase, biotite, garnet, sillimanite, K-feldspar.

KAW 183/184 Rhyolite, Permian volcanics of the southern Alps, Cava Bianchi, Cavagnano. Coord. 712,300/84,800, 440 m a.s.l. The rock consists of quartz, K-feldspar, acid plagioclase and biotite. The K-feldspar is pigmented by disperse hematite. The rock is full of myarolitic cavities. The lighter variety contains more quartz.

KAW 414 Phengite alkalifeldspar gneiss, Sesia-zone, micascisti eclogitici small quarry before reaching Lilianes, road into Gressoney-Valley. Coord. 4°38'/45°37' 660 m a.s.l. The rock contains quartz, partly strained (phengitic muscovite, plagioclase (albite), garnet. Pale blue amphibole, omphacite, zoisite and opaques as inclusions in the garnet are minor minerals. Macroscopically a greyish micascist.

KAW 415 Phengite alkalifeldspar gneiss, Sesia-zone, gneiss minuti. Small quarry W. Case Campagnola, Arnaz, Aosta. Coord. 4°43'/45°38' 410 m a.s.l. The rock contains albite, quartz, phengite. As minor minerals biotite, epidote, allanite, chlorite and rutile are found and as rare relicts omphacite and glaucophane. Macroscopically a banded isoclinally folded green augengneiss with darker layers richer in biotite and chlorite.

KAW 473 Omphacite phengite gneiss, Sesia-zone, micascisti eclogitici, northwest Quassolo, Aosta, road cut of autostrada Torino-Aosta. Coord. 4°37'/45°32' 250 m a.s.l. Major minerals are albite, omphacite, phengite, quartz, garnet and pale blue glaucophane. Zoisite and opaques are minor minerals. The omphacite is partially transformed into diablastic. Macroscopically a greenish very heterogeneous micarich gneiss in contact with more compact eclogite lenses and associated with marbles.

KAW 474 Banded phengite alkalifeldspar gneiss, Sesia-zone, micascisti eclogitici, S.E. Bard, Aosta, road cut of autostrada Aosta-Torino. Coord. 4°42'/45°36', 380 m a.s.l. Major minerals: albite, phengite, quartz, glaucophane (with rims of pale amphibole), omphacite (relicts, mostly transformed), garnet and chlorite. Epidote, zircon and opaques are minor minerals. Macroscopically a banded phengite gneiss.

KAW 475 Phengite-albite gneiss, Piemont-zone, gneiss di Verres N.W. Barme, Aosta. Coord. 4°45'/45°39'. The rock consists of a fine grained ground mass of albite, quartz, calcite, phengite, glaucophane and often zoned omphacite. Biotite, garnet, quartz, epidote and allanite can be distinguished eventually constituting a second generation. Macroscopically a fine-grained spotted phengite gneiss.

KAW 476 Phengite alcalifeldspar augengneiss, Sesia-zone, gneiss minuti. Little quarry near Gattinari, Gressoney-Valley. Coord. 663,900/63,900, 1200 m a.s.l. The rock consists of albite, quartz, phengite. Minor minerals are epidote, zircon and chlorite. Macroscopically a greenish banded augengneiss.

KAW 484 Pegmatite, Ivrea-zone, road from Candoglia, Toce, to the marble quarries. Coord. 676,800/92,400, 380 m a.s.l. The rock consists of K-feldspar, plagioclase, quartz, muscovite, turmaline, garnet, beryl, opaques. The muscovite flakes are in part extremely deformed.

KAW 485 Eclogite, Sesia-zone, micascisti eclogitici, Valle del Cervo, Lago Mucrone, Sesia. Coord. 4°30'/45°38', 1900 m a.s.l. The rock contains omphacite, garnet, phengite and glaucophane. Quartz, rutile, epidote and opaques are minor minerals. The euhedral garnet is zoned. A core rich in inclusions is surrounded by a purer rim. The inclusions are made up of quartz, omphacite, rutile and glaucophane. Macroscopically the rock is the massive core of an eclogite lense.

KAW 504 Micascisti, Strona-zone. Carmine inferiore, Lago Maggiore, road cut of Lake road. Coord. 698,100/99,650, 300 m a.s.l. The rock consists of plagioclase, quartz, biotite, muscovite. As minor minerals graphite, chlorite, garnet and zircon are found. The plagioclase is partially sericitized and quartz is strained. Macroscopically a two-mica schist with folded quartz veins.

KAW 505 Pegmatite, Ivrea-zone, S.E. Candoglia, pegmatites were quarried. Coord. 676,800/91,750, 210 m a.s.l. The rock consists of plagioclase, K-feldspar, quartz, muscovite, turmaline, garnet, beryl and opaques. The mica flakes are in part extremely deformed. Macroscopically a concordant pegmatoid schlieren in the micaschists of the Ivrea-zone.

KAW 506 Mica schist, Ivrea-zone. « Kinzigite » gneiss of the Italian authors. Country rock of KAW 505, same locality. Major minerals: plagioclase, quartz, biotite, muscovite and sillimanite. Graphite is a widespread minor mineral. Quartz shows randomly granular texture. Macroscopically a greyish micaschist.

KAW 507 Biotite gneiss, Ivrea-zone. New road cut of road Omegna-Germagnano, Valle Strona. Coord. 674,100/81,900, 500 m a.s.l. The rock consists of plagioclase, quartz, biotite, amphibole and microcline. As minor minerals allanite, graphite and zircon are found. Macroscopically a migmatic strongly heterogeneous gneiss.

KAW 558 Garnetiferous biotite-alkalifeldspar gneiss, Valpelline-nappe, Dent-Blanche-system. Small quarry S.W. Oyace, Valpelline, along the road from Aosta into the Valley. Coord. 594,900/76,600, 1150 m a.s.l. Major minerals: plagioclase, quartz, biotite and chlorite. Graphite, rutile, zircon and opaques are minor minerals. The garnet is broken, cracks are filled with quartz, plagioclase and biotite. Plagioclase is partly sericitized and quartz shows wavy extinction. Macroscopically a strongly folded banded gneiss with quartz-plagioclase veins.

KAW 560 Garnetiferous biotite-sillimanite gneiss, Valpelline nappe, Dent-Blanche system, S.W. Bionnaz, Valpelline. Main road. Coord. 597,950/79,700, 1580 m a.s.l. The rock consists of plagioclase, quartz, garnet, biotite and sillimanite. Minor minerals are graphite, allanite and opaques. Macroscopically a banded isoclinaly folded gneiss.

KAW 563 Phengite alkalifeldspar gneiss, Sesia-zone. Quarry Campo Albino, Toce. Coord. 685,800/97,550, 400 m a.s.l. The rock contains plagioclase, quartz, actinolite (seldom with cores of brown amphibole), phengite, zoisite, biotite and garnet. Minor minerals are graphite, zircon and apatite. Macroscopically a greenish fine grained augengneiss.

KAW 565 Biotite granite, Strona-zone. Quarry of Alzo, Madonna del Sasso, Orta. Coord. 672,800/71,100, 460 m a.s.l. The rock consists of plagioclase, quartz, K-feldspar (partly unmixed), biotite. As minor minerals zircon with big pleochroic halos and sericite in some of the K-feldspar is found. Macroscopically a coarse - grained white granite.

KAW 572 Micaschist, Strona-zone, road cut, Mergozzo, Toce. Coord. 678,900/90,500, 300 m a.s.l. Major minerals: plagioclase, quartz, biotite, muscovite and garnet. Graphite, zircon and apatite are minor minerals. Macroscopically a fine-grained micaschist with quartz veins.

KAW 599 Garnetiferous biotite-gneiss in granulite facies (« stronalite » of the Italian authors). Forno, Strona, road cut. Coord 665,000/87,800, 976 m a.s.l. The rock contains garnet, plagioclase (in part sericitized), quartz, K-feldspar (in part grid twined). Graphite, red brown biotite, sillimanite, zircon and opaques are minor minerals. This gneiss in granulite facies is very heterogeneous. Biotite is enriched in darker spots.

KAW 653 Chloritoid porphyroblasts in metagabbro of Piemont ophiolites of the Zermatt Saas-zone. Path Fluhalp-Pfulwe. Coord. 629,800/96,250, 2580 m a.s.l. The rock contains chloritoid, paragonite, glaucophane, chlorite, magnetite and rutile. In part the chloritoid has been transformed to paragonite and magnetite.

KAW 654 Eclogitic gabbro, Piemont ophiolites, Zermatt-Saas-zone. Path Fluhalp-Pfulwe. Coord. 630,500/96,150, 2700 m a.s.l. The rock contains omphacite, garnet, paragonite and rutile (as first generation?) Glaucophane (often substitutes omphacite and grows as rim around or in cracks of garnet), magnetite and albite are minor minerals of possibly later generation. Macroscopically a greenish, massive rock with euhedral garnets up to ∅ 1 cm. This rock constitutes the cores of the best preserved pillows in eclogite facies of this pillow lava complex.

KAW 655 Metagabbro at 10 m distance of 654. Major minerals: omphacite, glaucophane, garnet. Minor minerals: quartz, paragonite, zoisite and rutile. Glaucophane grows as rim around garnet and as big lath in the matrix. The omphacite is partially diablastic.

KAW 656 Glaucophane schist, Piemont ophiolites, Zermatt-Saas zone, path Fluhalp-Pfulwe. Coord. 630,950/96,150, 2800 m a.s.l. Major minerals are glaucophane, paragonite, chlorite, garnet and epidote. Omphacite, rutile, albite and opaques are minor minerals. Macroscopically a glaucophane schist with still recognizable gabbroic textures.

KAW 657 Amphibole glaucophane prasinite, chloritoid and paragonite bearing. Metagabbro, Piemont ophiolites, zone of Zermatt-Saas. E. path to Pfulwe. Coord. 631,350/96,150, 3120 m a.s.l. Under the microscope we see in a fine-grained groundmass of glaucophane, epidote, zoisite, albite, green amphibole, porphyroblasts of garnet (the cores rich in inclusions), chloritoid and big paragonite flakes.

KAW 658 Actinolite albite vein in KAW 657, 50 m W. of 657.

KAW 660 Glaucophane schist. 10 m aside of 656. The rock contains omphacite, garnet, glaucophane, albite, paragonite, chlorite and talk. Zoisite, rutile and magnetite are minor minerals. The omphacite is to the greatest part transformed to diablastic. Macroscopically a blueish relatively massive rock.

KAW 661 Glaucophane schist 15 m aside 656. The rock contains paragonite, glaucophane, garnet, chlorite, omphacite and chloritoid. Epidote, rutile and opaques are minor minerals. Macroscopically a white schist in which glaucophane and garnet are seen as knobs in the paragonite schist.

KAW 682 Biotite-sillimanite-alkalifeldspar gneiss, Valpelline nappe of the Dent-Blanche system, Prarayer, Valpelline. Coord. 606,250/85,000, 1950 m a.s.l. Major minerals: strained quartz, red brown biotite, plagioclase (in part sericitized in part myrmekitic), sillimanite and chlorite. Minor minerals: garnet, graphite and opaques.

KAW 683 Eclogite, micascisti eclogitici, Sesia-zone, Valle del Cervo, S. Lago Mucrone, Sesia. Coord. 4°30'/45°38', 1900 m a.s.l. Major minerals are: omphacite, garnet, phengite, glaucophane. Quartz, rutile, epidote and opaques are minor minerals. The euhedral garnet is zoned: a inclusion-rich core is surrounded by a purer rim. The inclusions are: quartz, omphacite, rutile and glaucophane. The rock is more or less massive but the phengite is enriched along discrete planes.
683 is the core of an eclogite lense, the rock shows very little transformation.

KAW 684 Glaucophane schist, same locality as 683. The rock contains glaucophane, omphacite, garnet. Epidote, phengite, rutile and opaques are minor minerals. Macroscopically: border of an eclogite lense. Parallel texture more pronounced.

KAW 685 Phengite schist (glaucophane, omphacite and garnet bearing), same locality as 683. The rock consists of phengite, quartz, chlorite and garnet. As minor minerals omphacite, glaucophane, sphene and opaques are found. Macroscopically the schistose country rock of the eclogite lense.

KAW 697 Trachyandesite (Oligocene) along the Insubric Line, Favaro, Sesia. Coord. 4°27'/45°36', 700 m a.s.l. The rock consist of plagioclase (andesine to labradorite), clinopyroxene, brown amphibole. Biotite, opaque minerals, apatite and calcite are minor minerals. Rock 697a is more transformed than 697b.

KAW 698 Micaschist, inclusion in trachyandesite of Favaro, same locality as 697. The rock contains phengite, quartz, plagioclase, garnet, chlorite and calcite. Rutile, relictic omphacite, glaucophane and opaques are minor minerals. Diameter of inclusion 698a = 25 cm, 698b = about 1 m.

KAW 699 Chlorite-sillimanite gneiss, Sesia-zone, II DK S.W. Riva Val Dobbia, Val Sesia. New road to Valvogna. Coord. 639,800/75,300, 1250 m a.s.l. The rock contains chlorite, quartz, plagioclase, sillimanite and graphite. As minor minerals muscovite, zoisite and opaques are found. The plagioclase is highly altered and full of sericite. Macroscopically a brown schistose gneiss.

KAW 700 Fine-grained biotite-phengite-bearing alkalifeldspar gneiss, Sesia-zone, gneiss minuti, Val Sesia, Isolello. Coord. 641,900/74,800, 1025 m a.s.l. Major minerals: plagioclase, quartz, K-feldspar. Minor minerals: biotite, phengite, chlorite, epidote, zoisite and omphacite. The K-feldspar is partly perthitic, partly grid twinned, quartz is mostly strained.

KAW 750 Glaucophane schist, Piemont ophiolites, Upper Zermatt-Schuppenzone. Alpe Berrio, Ollomont, Valpelline. Coord. 591,300/78,900, 2060 m a.s.l. The rock consists of quartz, plagioclase, glaucophane. Minor minerals are rutile and opaques. The plagioclase is in part full of inclusions and quartz shows two generations, coarser grains show wavy extinction while most of the quartz shows a fine-grained granular texture. The white schists are seen as wedges in the darker Arolla gneisses.

KAW 792 Eclogitic glaucophane schist, Piemont ophiolites, Zermatt-Saas zone, Lago Cignana Valtournanche, W.side of hydroelectric dam. Coord. 612,200/80,650, 2100 m a.s.l. Major minerals are glaucophane, omphacite, garnet and actinolitic hornblende. Minor minerals are rutile, epidote, calcite and opaques. The cores of the garnets are full of inclusions mainly omphacite, rutile and glaucophane. The glaucophane is often reduced to a rim around colourless hornblende. The omphacite is partially diablastic. Macroscopically a bluish massiv rock.

KAW 794 Glaucophane schist, Piemont ophiolites 2 km S.W. Ulzio, on road Ulzio-Madonna Catolivier. Small quarry in a pillow Breccia. Coord. 5°37,5'/45°02', 1150 m a.s.l. Major minerals: glaucophane and epidote. The rest of the minerals being so small and the degree of transformation so severe, they were not determinable. Macroscopically a very inhomogeneous rock - the pillows can still be recognized.

KAW 908 Rhyolite dyke (Permian), Strona-zone. Quarry Bolzano, Novarese, Orta. Coord. 677,700°69,400, 400 m a.s.l. Major minerals: in a fine-grained equigranular ground mass of quartz and plagioclase, big euhedral crystals of quartz, K-feldspar and plagioclase occur. Some of the K-feldspar is perthitic, in part the plagioclase in sericitized. Minor minerals are biotite, sericite, zircon, apatite and opaques. Macroscopically a massive reddish rock.

KAW 909 Rhyolite dyke (Permian) of tse Southern Alps (Strona-zone). Valsesia. N.W. Romagnano. Coord. 4°6'/45°49'. Major minerals: quartz, K-feldspar, plagioclase and biotite. Plagioclase and K-feldspar pigmented with hematite. The biotite is partially chloritized. Minor minerals: hematite, apatite and zircon. The quartz, plagioclase and K-feldspar are big euhedral crystals in a fine-grained groundmass of unidentifiable but not glassy composition. Macroscopically a red massive rock.

KAW 910 Rhyolite tuff (Permian), of the Southern Alps (Strona-zone). Country rock of 909, same locality. Major minerals: in an extremely fine-grained matrix quartz and plagioclase phenocrysts are seen together with bits of rhyolitic rock (but also of more basic volcanics). Primary glassy textures are in part still recognizable. Biotite, opaques and zircon are minor minerals. The K-feldspar is mostly sericitized.

KAW 912 Tuffite (Oligocene), along the Insubric Line, Sordevolo, Biella, Elvo river. Coord. 4°29'/45°34', 650 m a.s.l. In a fine-grained matrix basic plagioclase and grains of trachyandesite represent the volcanic parts. Quartz, phengite, chlorite, glaucophane, rutile, epidote, zoisite, graphite and garnet can be derived from the nearby Sesia basement. At Sordevolo the tuffite represents the base of the trachyandesitic sequence.

KAW 943 Glaucophane boudin in KAW 942 Bernhard-nappe. S. side of Mont Gelé. Coord. 587,800/104,950, 2950 m a.s.l. The rock consists of glaucophane, phengite, quartz and chlorite. As minor minerals apatite, zircon, epidote, rutile and opaques are found. The rock represents a fissure or boudin parallel to the main schistosity of the gneiss.

KAW 984 Phengite alcalifeldspar gneiss, Arolla nappe of the Dent Blanche system, Matterhorn S side. Coord. 616,900/89,250, 2600 m a.s.l. Major minerals: plagioclase (sometimes myrmekitic), strained quartz, phengite and hornblende (in part with brown cores). Chlorite, calcite, epidote and zircon are minor minerals. Macroscopically: a greenish gneiss.

KAW 988 Biotite granite, Sesia-zone, Monte Mucrone. Coord. 4°30'/45°37', 2000 m a.s.l. The rock contains as major minerals strained quartz, plagioclase (mostly transformed to jadeite and quartz), microcline (grid twinned), red brown biotite and garnet (rims around biotite). Opaques, rutile and zircon are minor minerals.

KAW 989 Eclogitic micaschist, Sesia-zone, quarry between Lago Mucrone and Oropa. Coord. 4°30'/45°38', 1700 m a.s.l. Major minerals are: omphacite, quartz, phengite, rutile and epidote. Minor minerals are: garnet, glaucophane and albite. This rocks suffered transformation from a granodiorite to an eclogitic rock by eo-Alpine metamorphism.

KAW 1063 Tuffite along the Insubric Line interlayered with trachyandesite 1064 Falletti. Sesia. Coord. 4°24'/45°39', 1100 m a. s. l. The tuffite shows graded bedding. In the fine grained layers SCHEURING *et al.* (1974 found a Tertiary flora. The rock consists of components of trachyandesites (with fresh basic plagioclase of intermediate optics), macroscopical plant remnants and minerals from the Sesia basement (quartz, phengite, omphacite, epidote, rutile, garnet and graphite).

KAW 1064 Trachyandesite (Oligocene) of the Insubric Line, same locality as 1063. Major minerals: plagioclase, clinopyroxene and brown amphibole. Biotite, opaques, apatite and calcite are minor minerals. All these minerals are found in an extremely fine-grained matrix. The high K-content of the rock reflects the possibility of a lot of microcrystalline K-feldspar in the matrix.

KAW 1068 Pegmatite, Quarona, new road cut, Val Sesia. Coord. 663, 800/65, 250, 400 m a. s. l. The rock consists of K-feldspar, plagioclase, quartz, muscovite, biotite, turmaline, garnet. Two generations of micas can be distinguished. The big mica fiakes are highly deformed and along the rims a second generation has grown.

For the other rocks, see references.

KAW 1117 = PB 032		
KAW 1118 = PB 543		
KAW 1121 = PB 1320		
KAW 1120 = PB 1302	}	P. BEARTH 1967
KAW 1122 = PB 1531		
KAW 1123 = PB 1536		
KAW 1124 = PB 1305		
KAW 1217 = F 43		
KAW 1218 = F 45		
KAW 1219 = F 74	}	R. WETZEL 1974
KAW 1220 = F 94		
KAW 1221 = F 111		
KAW 1222 = Hornblende Vogt, Standard Basel		

Coordinates according to map of F. HERMANN 1937 and the kilometer net of Landeskarte der Schweiz.

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ABSTRACT

Over 100 KAr and Rb-Sr determinations on minerals and rocks of 65 different samples of the Western Alps are presented.

The attempt is made to set up a time scale for the Alpine tectonics of the Western Alps using these data.

Three succeeding metamorphic and tectonic phases can clearly be distinguished.

1) Randomly oriented glaucophanes of the Mesozoic Piemont ophiolites and phengites of the Sesia zone are used to date the early Alpine high pressure low temperature phase in eclogite - blue schist facies at 80-100 m.y. (Eo-Alpine).

2) A later intermediate pressure intermediate temperature phase in green schist to amphibolite facies was dated by means of oriented glaucophanes, amphiboles and micas. (Lepontine phase 38 ± 2 m.y.).

3) Strongly oriented glaucophanes yield evidence for a Miocene phase of tectonics and recrystallisation around 20 m.y..

An attempt is made to incorporate the data into a plate tectonics model. According to this model the main Alpine tectonic phase of Austroalpine elements overthrusting Pennine elements is postulated already in the Upper Cretaceous times.

ZUSAMMENFASSUNG

An 65 verschiedenen Gesteinsproben aus den Westalpen wurden über 100 KAr und Rb-Sr Bestimmungen an Mineralien und Gesteinen durchgeführt. An Hand dieser Daten wurde der Versuch unternommen, die alpine Tektonik der Westalpen zeitlich zu unterteilen.

3 aufeinanderfolgende metamorphe und tektonische Phasen konnten klar unterschieden werden:

1) Ungeregelte Glaukophane der mesozoischen Ophiolithe des Piemontesischen Troges und Phengite aus der Sesia-Zone ergeben ein frühalpines Alter der Hochdruck-Niedertemperatur-Metamorphose in Eklogit - Glaukophanschieferfazies. (Eoalpine Phase 80-100 m.y.).

2) Die nachfolgende metamorphe Phase in Grünschiefer - Amphibolitfazies ist durch intermediären Druck und Temperatur gekennzeichnet. Alter an orientierten Glaukophanen, Alkaliamphibolen und Glimmern führen zur Festlegung der Lepontinischen Phase mit 38±2 m.y..
3) Stark orientierte Glaukophane miozänen Alters machen eine tektonische Phase um 20 m.y. wahrscheinlich.

Der Versuch wird unternommen, diese Daten in ein Plate-Tectonics-Modell einzubauen. Daraus folgt, dass die tektonische Hauptphase der alpinen Orogenese, die Ueberschiebung austroalpiner über penninische Elemente, schon in der Oberkreide erfolgte.

RÉSUMÉ

Dans ce travail sont présentées plus de 100 mesures d'âges K-Ar et Rb-Sr effectuées sur des minéraux et des roches, en tout 65 échantillons différents, provenant des Alpes occidentales.

A partir de ces données il est tenté d'établir une échelle chronologique pour la tectonique alpine des Alpes occidentales.

Trois phases métamorphiques et tectoniques successives se distinguent:

1) Des glaucophanes non orientés provenant des ophiolites mésozoïques piémontaises et des phengites de la zone Sesia fournissent un âge alpin précoce pour le métamorphisme de haute pression et basse température, dans un faciès éclogite-schiste bleu (phase éoalpine, environ 80-100 m.a.).
2) La phase suivante, de pression et température intermédiaires, dans un faciès de schiste vert à amphibolite, est datée grâce à des glaucophanes, des amphiboles et des micas orientés (phase lépontine, 38±2 m.a.).
3) Des glaucophanes fortement orientés indiquent une phase de tectonique et de recristallisation miocène, vers 20 m.a.

On essaie d'incorporer ces données dans un modèle de tectonique en plaques. D'après celui-ci la principale phase tectonique alpine au cours de laquelle les unités austro-alpines ont chevauché les unités penniques, aurait eu lieu déjà dans le Crétacé supérieur.

RIASSUNTO

Si espongono oltre cento determinazioni K-Ar e Rb-Sr di minerali e rocce provenienti da 65 località diverse delle Alpi occidentali. Questi dati sono utilizzati per ricostruire la cronologia dell'evoluzione tettonica e metamorfica delle Alpi occidentali.

Si distinguono chiaramente tre successive fasi tettonico-metamorfiche.

1) Il glaucofane non orientato delle pietre verdi mesozoiche della Zona piemontese e la fengite della Zona Sesia-Lanzo indicano che la fase eoalpina di alta pressione e bassa temperatura in facies eclogiti-scisti bleu è di 80-100 m.a.
2) Segue una fase metamorfica a pressione e temperatura intermedie con caratteri variabili dalla facies scisti verdi a quella anfibolitica. La sua età, indicata da glaucofane orientato, anfiboli e miche, è di 38±2 m.a. (fase lepontina).
3) Un terzo glaucofane, chiaramente lineato, mette in evidenza una fase miocenica con ricristallizzazione e deformazione attorno a 20 m.y..

Questi risultati sono discussi ed interpretati nel quadro della tettonica a placche secondo un modello nel quale, durante la principale fase tettonica alpina, gli elementi austroalpini sovrascorrono sopra quelli pennidici già nel Cretaceo superiore.

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