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K - AR AGES ON ROCK - FORMING MINERALS FROM THE CENTRAL ALPS

(with 2 figures, 3 tables and 2 plates)

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INTRODUCTION

From the Central and Western Alps there exist many Rb-Sr ages on biotites and muscovites (phengites), the number of mica K-Ar ages already published is much smaller. It has been previously emphasized that the Alps offer a unique region for a detailed study of isotopic ages because: the geology of the Alps has been well studied and the zones of the Lepontine metamorphism have been extensively described (for detailed information see the special volume of SMPM, 1974, with articles by AYRTON and RAMSAY; DIETRICH *et al.*, FREY; FREY *et al.*; E. NIGGLI; TROMMSDORFF and EVANS; H.R. WENK; H.R. WENK *et al.*). The likelihood is that the rocks have remained thermally undisturbed since the Lepontine phase of Alpine metamorphism, undisturbed also by fluid phases which played no dominant role during this metamorphic phase. Furthermore, young ages can be measured with small absolute errors, thus the resolution of dating different stages of metamorphic events is high.

Earlier work has shown that the Rb-Sr mica ages reflect the grade of Alpine metamorphism that the host-rock has undergone (JÄGER *et al.*, 1967, JÄGER and HUNZIKER, 1969). Briefly, within the staurolite isograd, with Alpine staurolite, kyanite and sillimanite, both muscovite and biotite give young Alpine ages; in the chloritoid zone, biotites from acidic rocks give Tertiary Alpine ages, while those from more basic rocks may preserve their pre-Alpine age. These pre-Alpine ages are either Hercynian or intermediate Alpine-Hercynian. In this zone, pre-Alpine muscovites retain their pre-Alpine ages, while the newly formed phengites and muscovites always give Tertiary ages. The crystallization of new muscovite and phengite does not influence the Rb-Sr age of the Hercynian muscovite; actually, both ages are found quite frequently on separated white mica phases from the same rock. In the inner stilpnomelane zone, biotite may give Alpine and intermediate Alpine-Hercynian ages, the pre-Alpine muscovite retaining its Hercynian age. In the outer stilpnomelane zone, only pre-Alpine mica ages were found.

The Hercynian ages must give the time when these minerals were last affected by the Hercynian orogeny, while the intermediate Alpine-Hercynian biotite ages probably represent « over-printed » ages, that is, the temperature of the Alpine metamorphism was sufficiently high to only partially remove the pre-Alpine radiogenic

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strontium. It is also possible that biotites give mixed ages because of the incomplete mineral separation of coexisting Alpine and pre-Alpine biotite. Alpine phengite can easily be separated from pre-Alpine muscovite, if both micas occur as isolated grains. Quite frequently, the two micas are intergrown, in this case a quantitative mineral separation is difficult, sometimes impossible. Thus the Rb-Sr age of the Alpine phengite might be too high, the pre-Alpine muscovite age too low.

The young Alpine ages have been given two different interpretations, depending upon the maximum temperature reached by the host-rock during the Alpine metamorphism. For those newly formed muscovites and phengites from rocks which did not go much above the formation temperature of these micas, max. about 500°C, these ages have been interpreted as formation ages. Further HUNZIKER, 1970, and JÄGER, 1973, have argued that these ages from the external Pennine areas date the climax of the last phase of Alpine metamorphism at 35-40 m.y. Biotites from these same rocks give ages younger than 38 m.y. and have been interpreted as cooling ages, that is, they date the time when the rock cooled to a temperature where the loss of radiogenic strontium ceased.

Biotites and muscovites (phengites) from rocks heated above the formation temperature of muscovite or phengite, i. e. above 500°C, give ages less than 38 ± 2 m.y. and have been interpreted as cooling ages. In the Simplon region, where it has been possible to obtain several precise coexisting biotite and muscovite ages, the muscovite or phengite is typically 7 to 8 m.y. older than biotite, indicating a higher closure temperature for muscovite than for biotite. JÄGER, 1973, has given arguments for the closure temperatures of muscovite and biotite, namely 500 ± 50°C and 300 ± 50°C respectively.

This fact, that different minerals close to a given radiogenic daughter loss at different temperatures, allows us with appropriate assumptions to calculate uplift rates between these two temperatures. S.P. CLARK, Jr. and JÄGER, 1969, combined the results of heat flow measurements of three tunnels in the Swiss Alps with Rb-Sr mica ages from the same region to deduce uplift values of the order of 0.4 to 1.0 mm/y over the past 35 m.y. WAGNER and REIMER, 1972, have deduced an uplift rate of 0.4 mm/y from apatite fission track ages for the Monte Rosa area. Also, they show from a regional distribution of the fission track data, corrected for the same altitude, that the area around the Simplon pass has undergone the latest, fastest uplift within the last million years, a conclusion reached earlier by JÄGER *et al.*, 1967, from the regional distribution of Rb-Sr biotite ages. More detailed information on the young uplift will be published by WAGNER *et al.*, also Mem. Ist. Geol. Min. Univ. Padova, in press.

As mentioned previously, there are few published K-Ar mica ages from the Central Alps. ARMSTRONG *et al.*, 1966, have shown that young Alpine biotites from the chloritoid and higher grade metamorphic zones generally give concordant Rb-Sr and K-Ar ages. One biotite from Zervreila, from the zone of Alpine chloritoid, gave a mixed Alpine-Hercynian Rb-Sr age of 175 ± 7 m.y. and a K-Ar age of 340 ± 20 m.y. Sample KAW 86 from the Monte Rosa gave a concordant mixed Alpine - Hercynian age, 91 ± 4 m.y. by the Rb-Sr method and 105 ± 10 m.y. by the K-Ar method.

Other K-Ar dates from this region have been published by JÄGER and FAUL, 1959, and HANSON *et al.*, 1966.

The present work will describe the results of a K-Ar investigation on 35 mica pairs including 5 whose coexisting plagioclase and potassium feldspar were also analysed. In addition, several single micas, mainly pegmatitic, have been analysed. The samples were selected from the tectonic units: Aare and Gotthard massives, Pennini nappes and the Bergell intrusion, from areas of different degrees of Alpine metamorphism. The two major points to be discussed will be the comparison of the Rb-Sr and K-Ar mica ages and the new information we deduce from the K-Ar data.

ANALYTICAL TECHNIQUES AND AGE RESULTS

The argon analyses were made by J. W. PURDY during his stay in Bern from 1968 to 1970. Argon was extracted *in vacuo* by induction heating of a molybdenum crucible containing about 200 mg of the purified mineral concentrate. The fusion furnace and both purification sections were constructed of quartz glass and pyrex; all metal bakeable valves used throughout. Before fusion of the samples commenced, highly enriched ^{38}Ar spike (> 99.98%) was metered directly into the extraction line via a double tap-reservoir system. The ^{38}Ar spike had been calibrated against known volumes of air argon. Initial purification of the gas sample was over hot (~ 850°C) titanium sponge and hot (~ 450°C) Cu-CuO mixture. After a second purification over hot titanium sponge, the argon sample was admitted directly to a Varian GD 150 mass spectrometer for analysis. This mass spectrometer has been described by PURDY, 1972, in connection with argon analyses. Mass discrimination was monitored by periodically analysing atmospheric argon purified in the argon line. The value measured for the 40/36– ratio was 292.4 with a standard error of 0.4%. Eight analyses on the standard muscovite KAW 4 M yielded a standard deviation of 1.1% (see Table I). In the meantime the precision has been improved by a factor of 2 with more reliable melting techniques and a better electronics stabilization.

Potassium concentrations were measured at least in duplicate with a Beckman flame photometer, using a hydrogen-oxygen flame. The sample solutions were admitted directly to the flame without any internal standard. To avoid matrix effects, a careful regulation of the flame temperature and dilution to less than 10 ppm potassium is necessary. Furthermore, the concentration of the hydrochloric acid (0.1 normal) must be kept constant. This method has been used only for potassium concentrations higher than 1%; for smaller contents, the isotope dilution technique is applied, using the ^{40}K- spike. 29 independent potassium determinations on the standard muscovite KAW 4M gave a mean K- content of 8.70%, with a standard deviation of 0.6%.

Of the eighteen samples analysed by ARMSTRONG *et al.*, 1966, eight have been repeated; for six of these repeat measurements the ages agree within the error limit. In all but one case (B 8), the atmospheric argon contaminations reported in the present study are significantly less than those reported earlier by ARMSTRONG *et al.*, 1966. The higher argon-blank of ARMSTRONG *et al.* was caused by fusing the sample

TABLE 1 - K-Ar Analytical Data and Age Results

Sample No	Locality	Rock	Mineral	% K	$^{40}Ar_{rad.}$ x 10^{-6} cm^3 STP/gr	% rad.	Age in m.y.
KAW 4 B	Brione/Verzasca	Verzasca gneiss	B	7.90	5.33±0.08 (*)	67.6±4.6	16.8 ± 0.7
KAW 4 M			M	8.70±0.05 (**)	6.32±0.07 (***)	54.7±3.1	18.1 ± 0.7
KAW 82	Croppo	gneiss of the root zone	B	7.71, 7.75	6.08, 6.10	64.4, 65.8	19.6 ± 0.8
			M	8.69, 8.72	8.10	65.4	23.2 ± 1.4
			Pl, Qz	0.286, 0.286, 0.294	0.639	61.6	54.7 ± 3.6
			KF	12.09, 12.16	9.58	87.8	19.7 ± 0.9
KAW 83	Beura	gneiss of the root zone	B	7.86, 7.93	6.76	81.4	21.3 ± 1.0
			M	8.84, 8.83	8.01, 7.95	85.1. 85.1	22.5 ± 0.9
			Pl, Qz	3.02	3.71	81.9	30.5 ± 1.5
			KF	11.13, 11.18	11.9	91.4	26.6 ± 1.2
KAW 93	tunnel Nalps-Curnera	ultrabasic inclusion	B	7.81, 7.84	120.1, 117.4, 119,6	97.5, 97.7, 97.1	347 ±14
KAW 105	Truzzo	Tambo granite-gneiss	B	7.84, 7.81	6.96	89.6	22.2 ± 1.0
			M	9.00, 8.95	21.3, 21.5	87.3, 87.9	58.8 ± 2.4
KAW 124	tunnel Nalps-Curnera	biotite-sill.-kyan.-gneiss	B	7.06, 7.07	119.7, 115.8, 115.9	98.0. 97.4, 95.4	376 ±15
KAW 125	tunnel Nalps-Curnera	quartz diorite	B	6.86, 6.91	110.0	97.3	363 ±15
KAW 126	tunnel Nalps-Curnera	rim around ultrabasic inclusion	B	7.64, 7.67	119.4, 117.1	97.7, 96.4	352 ±14
KAW 137	Osogna	Leventina gneiss	B	7.84, 7.89	5.04	69.7	16.0 ± 0.9
			M	8.83, 8.95	6.01, 6.12	75.1, 75.3	17.0 ± 0.7
KAW 138	Pollegio	Leventina gneiss	B	8.17, 8.14	5.74	62.6	17.6 ± 1.1
			M	8.97, 8.98	6.29, 6.21, 6.09	80.8, 72.8, 80.6	17.2 ± 0.7

(*) mean and standard deviation of 4 measurements
(**) mean and standard deviation of 29 measurements
(***) mean and standard deviation of 8 measurements
Minerals: B biotite, M muscovite, Ph phengite, Pl, Qz plagioclase + quartz, KF K-feldspar

TABLE 1a - K-Ar Analytical Data and Age Results

Sample No	Locality	Rock	Mineral	% K	$^{40}Ar_{rad.}$ x 10^{-6} cm^3 STP/gr	% rad.	Age in m.y.
KAW 140	Chiggiogna	Leventina gneiss	B	7.86, 7.86, 7.90	4.95	66.4	15.7 ± 1.2
			M	8.87	5.71	77.1	16.1 ± 0.8
KAW 146	Calanca	gneiss	B	7.13, 7.13	5.35	81.2	18.7 ± 0.9
			M	8.03, 8.17	6.22, 6.14, 6.05	65.7, 76.2, 67.2	18.9 ± 0.8
KAW 159	Gondo	Antigorio gneiss	B	8.03, 8.07	3.75	64.3	11.6 ± 0.7
			M	8.90, 8.96	4.96, 4.90	61.9, 66.0	13.8 ± 0.9
KAW 160	W of Gondo	Lebendun gneiss	B	8.22, 8.20	3.69	72.5	11.2 ± 0.6
			M	8.81, 8.79	5.12, 4.96, 4.89	74.0, 74.4, 66.6	14.2 ± 0.6
KAW 161	Simplon pass-road	Monte Leone gneiss	B	8.17, 8.26	4.00	76.3	12.2 ± 0.6
			M	8.96, 9.05	5.64	60.0	15.6 ± 1.0
KAW 162	Simplon pass-road	Berisal gneiss	B	7.13, 7.16	3.16	80.9	11.1 ± 0.5
			Ph	9.07, 9.09	6.76	80.7	18.6 ± 0.9
KAW 164	Simplon pass-road	Ganter gneiss	B	8.09, 8.08	4.46	74.6	13.8 ± 0.7
			Ph	9.03, 9.05	6.63	87.7	18.3 ± 0.8
KAW 165	Simplon pass-road	Eisten gneiss	B	7.95, 8.04	4.45	66.4	13.9 ± 0.8
			Ph	9.10, 9.00	6.58	83.7	18.1 ± 0.9
KAW 189	Soazza	Adula gneiss	B	7.84, 7.73	5.98	70.7	19.2 ± 1.1
			Ph	9.02, 8.90	7.66	81.0	21.3 ± 1.1
KAW 201	Baceno	Verampio granite gneiss	B	7.74, 7.74	4.00	68.8	12.9 ± 0.8
			M	8.77, 8.75	4.96	72.0	14.1 ± 0.8
			Pl, Qz	0.530, 0.530, 0.531	0.493	26.3	23.2 ± 3.5
			KF	12.01, 12,07	4.12	73.1	8.56 ± 0.47
KAW 203	Fibbia	Fibbia granite gneiss	B	7.62, 7.73	5.16	64.3	16.8 ± 1.0
			Ph	9.09, 9.09	6.82	71.5	18.7 ± 1.0

Table 1b - K-Ar Analytical Data and Age Results

Sample No	Locality	Rock	Mineral	% K	$^{40}Ar_{rad.}$ x 10^{-6} cm^3 STP/gr	% rad.	Age in m.y.
KAW 281	Promontogno	Tambo gneiss	B	6.77, 6.76	7.87	72.5	28.9 ± 1.6
			M	7.57, 7.58	13.20	85.6	43.2 ± 2.0
KAW 286	Cascata Toce	Lebendun gneiss	B	7.77, 7.78	4.53	52.7	14.6 ± 1.1
			M	8.59, 8.58	5.70	60.8	16.6 ± 1.1
			Pl, Qz	0.486, 0.482	0.684	24.9	35.1 ± 5.6
			KF	11.96, 11.94	6.07	50.9	12.7 ± 1.0
KAW 311	Gerental	Rotondo granite	B	7.59, 7.60	5.15	77.1	16.9 ± 0.9
			Ph	8.67, 8.66	8.80	81.2	25.3 ± 1.2
			Pl, Qz	1.29	2.65	75.8	50.8 ± 2.7
			KF	11.39, 11.38	14.62	86.9	31.9 ± 1.5
KAW 358	Serra	Lebendun gneiss	B	7.85, 7.84	3.88	68.7	12.4 ± 0.7
			M	8.76, 8.80	5.23	76.5	14.9 ± 0.8
KAW 359	Massa-tunnel	biotite-gneiss	B	8.00	4.56	79.2	14.2 ± 0.7
KAW 370	Bränd	Bernhard gneiss	B	7.87, 7.90	8.24	79.3	26.0 ± 1.3
			M	8.36, 8.39	10.8	87.1	32.1 ± 1.5
KAW 371	Anzasca	Monte Rosa gneiss	B	7.21, 7.29	6.41	69.6	22.0 ± 1.3
			Ph	9.09, 9.08	12.4	84.7	33.9 ± 1.6
KAW 372	Torno Bognanco	Monte Leone gneiss	B	8.00, 7,97	4.53	71.3	14.2 ± 0.8
			M	8.90, 8.90	5.78, 5.93	66.1, 60.1	16.4 ± 1.0
KAW 378	Randa	Bernhard gneiss	B	6.74, 6.78	11.08, 10.89	81.4, 84.1	40.3 ± 1.9
			Ph	9.10, 9.19	14.48	87.8	39.3 ± 1.8
KAW 399	Nanztal	Monte Leone gneiss	B	8.03, 8.00	4.43	71.6	13.8 ± 0.8
			Ph	8.73, 8.72	6.09	80.3	17.4 ± 0.9
KAW 400	Nanztal	Monte Leone gneiss	B	6.15, 6.15	3.15	42.1	12.8 ± 1.2
			Ph	9.13, 9.09	7.07	81.5	19.4 ± 1.0

TABLE 1c - K-Ar Analytical Data and Age Results

Sample No	Locality	Rock	Mineral	% K	$^{40}Ar_{rad.}$ x 10^{-6} cm^3 STP/gr	% rad.	Age in m.y.
KAW 401	Nanztal	Monte Leone gneiss	B	7.39, 7.36	4.23	70.9	14.3 ± 0.8
			Ph	9.11, 9.04	7.88	83.3	21.6 ± 1.0
KAW 405	Passo Mte Moro	Monte Rosa orthogneiss	B	7.94, 7.91	9.10	79.3	28.6 ± 1.4
			M	9.07, 9.10	13.4	87.4	36.6 ± 1.7
KAW 407	Bränd	Bernhard gneiss	B	7.48, 7.50	6.12	69.7	20.4 ± 1.2
			M	8.90, 9.00	10.1	85.5	28.1 ± 1.3
KAW 410	Wera	Bernhard gneiss	B	7.93	6.86	76.5	21.6 ± 1.0
			M	8.74, 8.75	8.20	81.4	23.4 ± 1.1
KAW 552	Val Piana	pegmatite	B	7.43, 7.35	6.90	64.8	23.3 ± 1.4
			M	7.31, 7.29	7.07	75.3	24.1 ± 1.3
KAW 553	Codera	Codera granite	B	7.21, 7.21	6.32	73.1	21.8 ± 1.2
			M	8.78, 8.73	7.90, 7.75	73.1, 80.0	22.3 ± 1.1
B 1	Pizzo Cocco	Cocco gneiss	B	7.77	6.04	70.2	19.4 ± 1.1
B 2	Lavertezzo	pegmatite	M	8.86, 8.96	6.75	63.0	18.9 ± 1.2
B 3			B	8.03, 8.07	5.33	70.6	16.5 ± 0.9
B 7	Riveo	Antigorio gneiss	B	8.13, 8.14	4.98	62.5	15.3 ± 1.0
B 8	Gordemo	gneiss of the root zone	B	7.82, 7.73	6.02	58.2	19.3 ± 1.3
			M	8.99, 8.93	6.89	75.2	19.2 ± 1.0
B 9	Lavertezzo	pegmatite	M	8.72, 8.80	6.81	57.0	19.4 ± 1.4
B 11	Monte Odro	pegmatite	M	9.09, 9.04	6.90	79.4	19.0 ± 1.0
B 37	Auressio	pegmatite	M	8.91, 8.86	6.80	53.2	19.1 ± 1.4

TABLE 2 - Rb-Sr and K-Ar Ages of Mica Pairs and Micas from Pegmatites

Sample No	Locality	Mineral	Rb-Sr age uncorrected	Rb-Sr age[+)] corrected	K-Ar age	K-Ar age difference (m.y.)[++)]
KAW 4 B	Brione	B	16.8 ± 0.5*)	—	16.8 ± 0.7	1.3
		M	—	—	18.1 ± 0.7	
KAW 82	Croppo	B	19.3 ± 0.7	18.7 ± 0.6	19.6 ± 0.8	3.6
		M	37.5 ± 7	26 ± 6	23.2 ± 1.4	
KAW 83	Beura	B	21.1 ± 1.3	20.1 ± 1.1	21.3 ± 1.0	1.2
		M	35 ± 7	28 ± 6	22.5 ± 9	
KAW 93	Nalps-Curnera	B	266 ± 11		347 ± 14	
KAW 105	Truzzo	B	25.2 ± 1.0	24.4 ± 1.0	22.2 ± 1.0	36.6
		M	238 ± 10	—	58.8 ± 2.4	
KAW 124	Nalps-Curnera	B	54 ± 8	51 ± 7	376 ± 15	
KAW 125	Nalps-Curnera	B	22.7 ± 2.0	—	363 ± 15	
KAW 126	Nalps-Curnera	B	164 ± 7	—	352 ± 14	
KAW 137	Osogna	B	17.3 ± 2.5	17.6 ± 1.9	16.0 ± 0.9	1.0
		M	—	—	17.0 ± 0.7	
KAW 138	Pollegio	B	16.7 ± 1.1	16.1 ± 0.9	17.6 ± 1.1	– 0.4
		M	30 ± 17	18 ± 13	17.2 ± 0.7	
KAW 140	Chiggiogna	B	16.5 ± 0.9	15.9 ± 0.7	15.7 ± 1.2	0.4
		M	26 ± 10	18 ± 8	16.1 ± 0.8	
KAW 146	Calanca	B	20.5 ± 4.1	17.7 ± 3.2	18.7 ± 0.9	0.2
		M	—	—	18.9 ± 0.8	
KAW 159	Gondo	B	11.4 ± 1.7	11.4 ± 1.3	11.6 ± 0.7	2.3
		M	—	—	13.8 ± 0.9	
KAW 160	W Gondo	B	11.7 ± 1.4	11.0 ± 1.1	11.2 ± 0.6	3.0
		M	22 ± 9	17 ± 8	14.2 ± 0.6	
KAW 161	Simplon	B	11.3 ± 1.3	11.0 ± 1.0	12.2 ± 0.6	3.4
		M	—	—	15.6 ± 1.0	
KAW 162	Simplon	B	14.1 ± 1.7	11.7 ± 1.4	11.1 ± 0.5	7.5
		Ph	27.7 ± 5.7	19.9 ± 4.7	18.6 ± 0.9	
KAW 164	Simplon	B	12.8 ± 2.3	11.7 ± 1.8	13.8 ± 0.7	4.5
		Ph	24 ± 12	21 ± 11	18.3 ± 0.8	
KAW 165	Simplon	B	13.5 ± 2.6	6.2 ± 2.0	13.9 ± 0.8	4.2
		Ph	26.1 ± 3.6	16.7 ± 2.9	18.1 ± 0.9	
KAW 189	Soazza	B	22.0 ± 3.6	18.4 ± 2.7	19.2 ± 1.1	2.1
		Ph	41 ± 15	26 ± 11	21.3 ± 1.1	
KAW 201	Baceno	B	14.0 ± 0.6	13.4 ± 0.5	12.9 ± 0.8	1.2
		M	18.6 ± 2.3	15.0 ± 1.9	14.1 ± 0.8	
KAW 203	Fibbia	B	16.0 ± 1.9	14.6 ± 1.5	16.8 ± 1.0	1.9
		Ph	27 ± 10	20 ± 8	18.7 ± 1.0	

+) age value of the mica - total rock isochron

++) K-Ar age differences: muscovite, phengite - biotite

*) mean and standard deviation of 13 measurements

TABLE 2a - Rb-Sr and K-Ar Ages of Mica Pairs and Micas from Pegmatites

Sample No	Locality	Mineral	Rb-Sr age uncorrected	Rb-Sr age+) corrected	K-Ar age	K-Ar age difference (m.y.)++)
KAW 281	Promontogno	B	29.6 ± 1.4	24.0 ± 1.1	28.9 ± 1.6	14.3
		M	49.5 ± 3.3	35.5 ± 2.7	43.2 ± 2.0	
KAW 286	Cascata Toce	B	14.7 ± 1.0	13.6 ± 0.8	14.6 ± 1.1	2.0
		M	25.8 ± 5.5	19.0 ± 3.0	16.6 ± 1.1	
KAW 311	Gerental	B	15.7 ± 0.6	14.5 ± 0.6	16.0 ± 0.9	8.4
		Ph	40.0 ± 1.6	36.6 ± 1.4	25.3 ± 1.2	
KAW 358	Serra	B	12.7 ± 0.7	11.9 ± 0.6	12.4 ± 0.7	2.5
		M	23.3 ± 3.4	19.0 ± 2.8	14.9 ± 0.8	
KAW 359	Massa	B	10.4 ± 2.9	10.3 ± 2.3	14.2 ± 0.7	
KAW 370	Bränd	B	22.2 ± 6.6	17.4 ± 5.0	26.0 ± 1.3	6.1
		M	—	—	32.1 ± 1.5	
KAW 371	Anzasca	B	27.3 ± 3.6	15.8 ± 2.9	22.0 ± 1.3	11.9
		Ph	41.7 ± 1.8	37.4 ± 1.5	33.9 ± 1.6	
KAW 372	Torno Bognanco	B	15.4 ± 0.6	14.4 ± 0.6	14.2 ± 0.8	2.2
		M	27.8 ± 2.2	21.1 ± 1.7	16.4 ± 1.0	
KAW 378	Randa	B	37.4 ± 1.6	31.7 ± 1.4	40.3 ± 1.9	1.1
		Ph	45.9 ± 2.4	35.4 ± 2.0	39.3 ± 1.8	
KAW 399	Nanztal	B	17.2 ± 2.9	10.3 ± 2.3	13.8 ± 0.8	3.6
		Ph	—	—	17.4 ± 0.9	
KAW 400	Nanztal	B	22.6 ± 6.3	0	12.8 ± 1.2	6.6
		Ph	33.7 ± 4.3	21.4 ± 3.4	19.4 ± 1.0	
KAW 401	Nanztal	B	23.4 ± 3.5	11.0 ± 2.8	14.3 ± 0.8	7.3
		Ph	46 ± 8	25 ± 6	21.6 ± 1.0	
KAW 405	Mte. Moro	B	29.9 ± 1.2	28.8 ± 1.1	28.6 ± 1.4	8.0
		M	51 ± 8	38 ± 6	36.6 ± 1.7	
KAW 407	Bränd	B	28 ± 10	22 ± 8	20.4 ± 1.2	7.7
		M	—	—	28.1 ± 1.3	
KAW 410	Wera	B	20.9 ± 4.3	19.0 ± 3.3	21.6 ± 1.0	1.8
		M	—	—	23.4 ± 1.1	
KAW 552	Val Piana	B	22.3 ± 1.8	20.3 ± 1.4	23.3 ± 1.4	0.8
		M	26.4 ± 1.2	25.4 ± 1.0	24.1 ± 1.3	
KAW 553	Codera	B	21.9 ± 2.7	21.3 ± 2.1	21.8 ± 1.2	0.5
		M	27 ± 12	24 ± 9	22.3 ± 1.1	
B 3	Lavertezzo	B	18.5 ± 1.9	—	16.5 ± 0.9	2.4
B 2		M	26.6 ± 4.6	—	18.9 ± 1.2	
B 8	Gordemo	B	19.8 ± 2.0	19.2 ± 1.6	19.3 ± 1.3	– 0.1
		M	—	—	19.2 ± 1.0	
B 9	Lavertezzo	M	21 ± 6	—	19.4 ± 1.4	
B 11	Monte Odro	M	19.7 ± 0.8	—	19.0 ± 1.0	
B 37	Auressio	M	28 ± 14	—	19.1 ± 1.4	

+) age value of the mica - total rock isochron

++) K-Ar age differences: muscovite, phengite - biotite in a glass furnace; at this time, 1965, we did not have induction heating. Therefore the precision of the argon determinations of this paper is much better. As sample KAW 82, biotite from Croppo, shows, the discrepancy between the earlier published K-Ar age (17.0 m.y. with argon rad. = 25%) and the new value (19.6 ± 0.8 m.y. with argon rad. = 65%) must be due to the high argon blank of the earlier analyses. The higher biotite age of sample KAW 105, Truzzo, analysed by ARMSTRONG *et al.*, was the result of incomplete mineral separation. Other minerals of the same rock, such as muscovite, have not been completely reset by the Alpine metamorphism, giving older ages. Thus the biotite K-Ar age is sensitive to contamination with other minerals. In the repeat analysis the potassium concentration is higher, 7.83% compared to 7.17% found by ARMSTRONG *et al.*; this changed the biotite ages considerably, from 29 to 22.2 ± 1.0 m.y.

The K-Ar analytical data and age results on the analysed samples and the Brione standards muscovite KAW 4 M and biotite KAW 4 B are summarized in Table I. In Table II the K-Ar ages on mica pairs and pegmatitic micas are compared with the Rb-Sr results of the same mineral concentrates.

The following decay constants were used:

$$^{87}Rb: \quad \lambda = 1.47 \times 10^{-11} y^{-1}$$

$$^{40}K: \quad \lambda_{\varepsilon} = 0.585 \times 10^{-10} y^{-1}$$

$$\lambda_{\beta} = 4.72 \times 10^{-10} y^{-1}$$

Errors quoted on the ages are calculated with the following formula:

$$\text{Error in m.y.} = \frac{\text{age} \times 4}{\%\ \text{rad.}}$$

This means that a minimum error of $\pm$ 4% is given for measurements with small contributions of air argon; if the argon extracted is less radiogenic, the error increases.

In Table II two sets of Rb-Sr ages are presented: « uncorrected » and « corrected » age results. The « uncorrected » ages have been calculated with a normal $^{87}Sr/^{86}Sr$ ratio for the non-radiogenic strontium component. « Corrected » ages represent the age values of the mineral-total rock isochron. For the meaning of these ages see the following chapters.

K-Ar AND Rb-Sr MINERAL AGES IN ALPINE METAMORPHIC ZONES

Before giving an interpretation of the regional distribution of K-Ar ages, a discussion will be given of the systematics of K-Ar and Rb-Sr mineral ages in two Alpine metamorphic regions; namely, within the staurolite zone (staurolite-kyanite-sillimanite) and in the chloritoid zone. In the lower grade regions (inner and outer stilpnomelane zones) the data are too few for meaningful comparisons.

The regional distribution of the K-Ar ages is shown in two maps, Plate I for the biotite and Plate II for the muscovite and phengite K-Ar ages. Both maps give the main tectonic units and the boundaries of the metamorphic minerals: stilpnomelane, chloritoid, staurolite, as well as two boundaries of 70% and 85% anorthite in plagioclase coexisting with calcite. For tectonics and Alpine metamorphic mineral boundaries we use the map as published by JÄGER *et al.*, 1967. The color of the sample points represents the age value, numbers on both maps indicate the sample numbers which are also given in both tables.

Although much more information on Alpine metamorphic minerals has in the meantime been published (see the special volume of Schweiz. Min. Petr. Mitt. 1974 « Alpidische Metamorphosen in den Alpen » with the papers: AYRTON and RAMSAY; DIETRICH *et al.*, FREY; FREY *et al.*, E. NIGGLI; TROMMSDORFF and EVANS; H. R. WENK; H. R. WENK *et al.*; and the Metamorphic Map of the Alps, compiled by E. NIGGLI, 1973) the general pattern of metamorphic zones and tectonics has not changed much. The use of the map already published by JÄGER *et al.*, 1967, permits the direct comparison with other age results presented on the same map: GRAUERT *et al.*, 1969, JÄGER and HUNZIKER, 1969, and PURDY and STALDER, 1973. The new fission track data on apatite by WAGNER *et al.*, in press, will also be published on the same map.

Fig. 2 is a simplified tectonic map with the K-Ar age differences between coexisting muscovite (phengite) and biotite; the numbers indicate age differences in m.y.

STAUROLITE ZONE - AMPHIBOLITE FACIES

HOSCHEK (1967) studied reactions in which staurolite forms from chloritoid. He found an equilibrium temperature of 545 ± 15°C, more or less independent of pressure. Similar results were obtained by RICHARDSON, 1968. Hence rocks within the staurolite isograd must have been above these temperatures during the Alpine metamorphism. Further, E. WENK, 1943, has shown that the Alpine metamorphism was sufficiently intense in many parts of this region to cause recrystallization of the micas.

Within the boundary of Alpine staurolite, the relationship between Rb-Sr and K-Ar *biotite* ages is quite simple; the ages agree within experimental error. The Rb-Sr biotite ages have been calculated with the data from the total rock and the separated biotite, they represent a biotite- total rock isochron. This procedure tacitly assumes that the strontium was isotopically homogenized throughout the total rock sample during the Alpine metamorphism. JÄGER, 1970, has shown from a Rb-Sr study of the total rock and separated minerals of samples KAW 286, 201, 82 and 83, all from the area of Alpine staurolite (see FREY, 1974) that the Alpine metamorphism caused a homogenization of the strontium isotopes among all constituent minerals.

It has not been possible to compare every Rb-Sr and K-Ar *muscovite* or *phengite* age within the staurolite zone. This is because the muscovite frequently contains too much common strontium to permit an accurate determination of the radiogenic ^{87}Sr component. In those cases where it has been possible to measure a Rb-Sr muscovite age, we find that it is higher than the K-Ar age. In fact, within the staurolite zone, in all cases where age discordances have been precisely measured, we find:

Rb-Sr (musc., pheng.) > K-Ar (musc., pheng.) > Rb-Sr (biot.) = K-Ar (biot.).

The K-Ar ages of both the biotites and muscovites or phengites from within the staurolite zone are interpreted as cooling ages. Concordance of K-Ar and Rb-Sr ages in biotites is taken to indicate that this mineral closes to radiogenic strontium and argon loss during the cooling period at the same temperature and the strontium isotopes were homogenized throughout the total rock during the Alpine metamorphism.

A similar type of age pattern was reported earlier by Hart, 1964, and Hanson and Gast, 1967, for micas involved in a contact metamorphic event. Although the results are similar, they reflect the conditions of two different metamorphic environments; a major difference being the time that the rocks remained at high temperatures. In the contact metamorphic case, this time is probably measured in hundreds of thousand of years, whereas in the regionally metamorphosed areas high temperatures (above 500°C) may have been sustained for more than 10 m.y. The ages themselves give different information: in the case of Hart (1964) and Hanson and Gast (1967) the measured age is composed of two parts, the time interval from today to the time of the metamorphism plus the « age » which was not erased at the time of the metamorphism. In the present study, the mica age gives us the time after the climax of the metamorphism, when the rock reached the closure temperature for the appropriate daughter nuclide.

An important result for mica ages from within the staurolite isograd is that, locally, the age is not a function of the grain size. This is most clearly seen in Val Verzasca where the pegmatitic muscovite K-Ar ages agree (samples B 37, B 9, B 11 and B 2), not only with each other, but with the finer grained rock muscovite from the same region (sample B 8). The grain size varies from several centimeters in diameter for the pegmatitic mica books to a size of several millimeters. Jäger *et al.*, 1967, had earlier remarked that large mica books from Alpine fissures and from the medium grained Simplon gneisses gave identical Rb-Sr ages, a result also true for K-Ar ages (Purdy and Stalder, 1973). This independence of grain size is to be contrasted with the « overprinting » results of Hart, 1964, and Hanson and Gast, 1967. This fundamental difference between cooling ages and overprinted ages may be connected with the differences in time that the micas were at higher temperatures.

Based on the experimental data of Hofmann and Giletti, 1970, Dodson, 1973, developed a diffusion model to evaluate the blocking temperature for Rb-Sr on biotite, assuming young Alpine ages of 10 and 20 m.y. resp., with linear cooling rates. Although the proposed blocking temperatures of 300°C for a 10 m.y. old biotite and 280°C for an age of 20 m.y. agree perfectly with our interpretation, the observed independence on the mineral grain size raises some doubt whether the rejuvenation during the cooling period really is due to a diffusion mechanism.

From four samples from the staurolite zone (samples KAW 82, 83, 201 and 286) *plagioclase* and *potassium feldspar* were analysed as well as the micas. All these feldspar concentrates had been studied earlier with the Rb-Sr method (Jäger, 1970), they all show Alpine Sr-homogenization within the rock sample. The K-Ar ages of the potassium feldspar do not indicate any systematic trend. They are in one case younger than the Rb-Sr biotite age (KAW 201), in two cases they cannot be distinguished from the biotite age, and in one case (KAW 83) the K-Ar age of the potassium feldspar is higher than the biotite age, even higher than the Rb-Sr age on muscovite. Thus the potassium feldspar seems to date a rather late stage of cooling, perhaps with a tendency to accept excess argon.

The plagioclase concentrates all contain some quartz. This may be the reason for the relatively high K-Ar age on the plagioclase concentrate of sample KAW 82, 54.7 ± 3.6 m.y., which is older than the climax of the Lepontine phase of metamorphism. It is well known that quartz easily accepts excess argon in metamorphic rocks, see Rama *et al.*, 1965. In all the four samples analysed by the K-Ar method, the plagioclase ages are higher than the potassium feldspar and mica ages, they all may be too high because of excess argon.

CHLORITOID ZONE - GREENSCHIST FACIES

In the chloritoid zone, micas may give Alpine, mixed Alpine-Hercynian or Hercynian ages. The Rb-Sr and K-Ar ages of a given biotite may or may not be concordant.

Alpine *biotite* ages (Rb-Sr and K-Ar) from the chloritoid zone show a different effect from those within the staurolite zone. For some of these biotites there is a discordance between the K-Ar and the « corrected » Rb-Sr age (samples KAW 165, 281 and 311). The « corrected » Rb-Sr age is calculated by using the data of both the whole rock and the biotite, it represents the age result of the biotite-total rock isochron. If instead, we correct for non-radiogenic strontium by using a normal $^{87}Sr/^{86}Sr$ ratio or the $^{87}Sr/^{86}Sr$ initial ratio of the pre-Alpine total rock isochron, concordance of the Rb-Sr and K-Ar biotite ages is achieved. Sample KAW 165 shows this effect most emphatically: the age calculated from the whole rock and the biotite, the « corrected » age, is 6.2 ± 2.0 m.y., whereas the age calculated with normal $^{87}Sr/^{86}Sr$ of 0.709 is 13.5 ± 2.6 m.y., which is in agreement with the K-Ar age of 13.9 ± 0.8 m.y.; for this sample no other interpretation is possible. The higher K-Ar biotite age of sample KAW 281 could also be explained by excess argon, as is indicated by the high muscovite K-Ar age of 43.2 ± 2.0 m.y., again an age older than the climax of the Lepontine phase. Other biotites from the chloritoid zone show the same discordance, though less strikingly, and sometimes difficult to resolve because of the poorer accuracy of the Rb-Sr ages.

In some of the samples (KAW 371, 399 and 400) the K-Ar ages lie in between the « corrected » and the « uncorrected » Rb-Sr ages. In these cases we assume the meaningful age again to be the K-Ar age; the Rb-Sr age should be calculated with a $^{87}Sr/^{86}Sr$ ratio in between the normal and the total rock value to achieve concordance between the K-Ar and Rb-Sr biotite ages. For example, one of the most extreme cases involves sample KAW 400, which gives a zero Rb-Sr « corrected » age, compared to the K-Ar biotite age of 12.8 ± 1.2 m.y. By using 0.709 for the $^{87}Sr/^{86}Sr$ ratio of the non-radiogenic strontium, the biotite age would be 22.6 ± 6.3 m.y., higher than the K-Ar age. In this case, concordance between the K-Ar and the Rb-Sr biotite age can be achieved by using an intermediate $^{87}Sr/^{86}Sr$ ratio, a value higher than 0.709

and lower than the total rock ratio, for the calculation of the non-radiogenic strontium in biotite.

An explanation of the above described behavior of biotites from the chloritoid zone is that these biotites lost their previously acquired radiogenic ^{87}Sr during the Alpine metamorphism, but did not or only partly exchange their « common strontium » with the whole rock. On cooling from the temperature climax, the biotites began to retain in situ produced radiogenic strontium (and argon) at 300°C, hence the better agreement between the K-Ar and the Rb-Sr ages if we use 0.709 to correct for the non-radiogenic strontium. Actually, as SATIR, 1974, proposed, we should use the initial $^{87}Sr/^{86}Sr$ ratio of the pre-Alpine, in many cases Hercynian, total rock isochron. But since this value usually is not very different from 0.709, it makes no difference which of these ratios is used.

This apparent lack of Sr-homogenization should therefore be checked by analysing all the minerals with the Rb-Sr method and not just the micas. But even so, the explanation of the data may not be easy. Regarding sample KAW 311, the biotite does not seem to have completely exchanged its non-radiogenic strontium with the other minerals or the total rock sample, although the minerals plagioclase, potassium feldspar, epidote and garnet did homogenize their strontium; only apatite did not, see JÄGER, 1970.

The same effect of preferential loss of radiogenic ^{87}Sr from the biotite has been demonstrated by SATIR, 1974, in a granite from the Tauern, Eastern Alps. We realize that this interpretation has important consequences when describing the parent-daughter system in different minerals used for dating. SATIR had to give the same interpretation for Rb-Sr ages on biotites from a different type of rock, different environment and based on Rb-Sr biotite age discordancies in rocks from a small area. Thus we believe that we can present good evidence for such a preferential loss of ^{87}Sr radiogenic from the biotite crystal, without affecting, or affecting only to some extent, the non-radiogenic strontium.

As mentioned above, not all the discrepancies between the K-Ar and Rb-Sr biotite ages can be explained by the above described effect. Some of the K-Ar ages on biotites (samples KAW 359, 370 and 378) are considerably higher than the Rb-Sr ages calculated with common strontium, the « uncorrected » Rb-Sr ages. The K-Ar biotite age of sample KAW 378 is too high, it is again higher than the age of the climax of the Lepontine phase of metamorphism, namely 40.3 ± 1.9 m.y. These high biotite K-Ar ages seem to be caused by excess argon. PURDY and STALDER, 1973, could demonstrate that, even in Alpine fissures, biotite and adularia from the same zone of metamorphism can take up excess argon in considerable amounts.

We have analysed only one plagioclase-quartz mixture and one potassium feldspar (KAW 311) from the chloritoid zone. The K-Ar age of the plagioclase-quartz concentrate is 50.8 ± 2.7 m.y., again « older » than the Lepontine metamorphism. This age has to be explained by excess ^{40}Ar, the high potassium feldspar age of 31.9 ± 1.5 m.y. could again be influenced by excess argon. This raises some doubt whether for this sample the above mentioned interpretation of the biotite age discordance is correct, the higher K-Ar age of biotite could also be caused by some excess argon in the biotite.

This example shows that, in the chloritoid zone, the interpretation of the biotite K-Ar and Rb-Sr ages is difficult because two effects are found here: excess ^{40}Ar in different minerals and incomplete Sr-homogenization. A clearer understanding of both strontium and argon movement in the chloritoid metamorphic zone would be achieved by a more detailed analysis of all the constituent minerals by both methods.

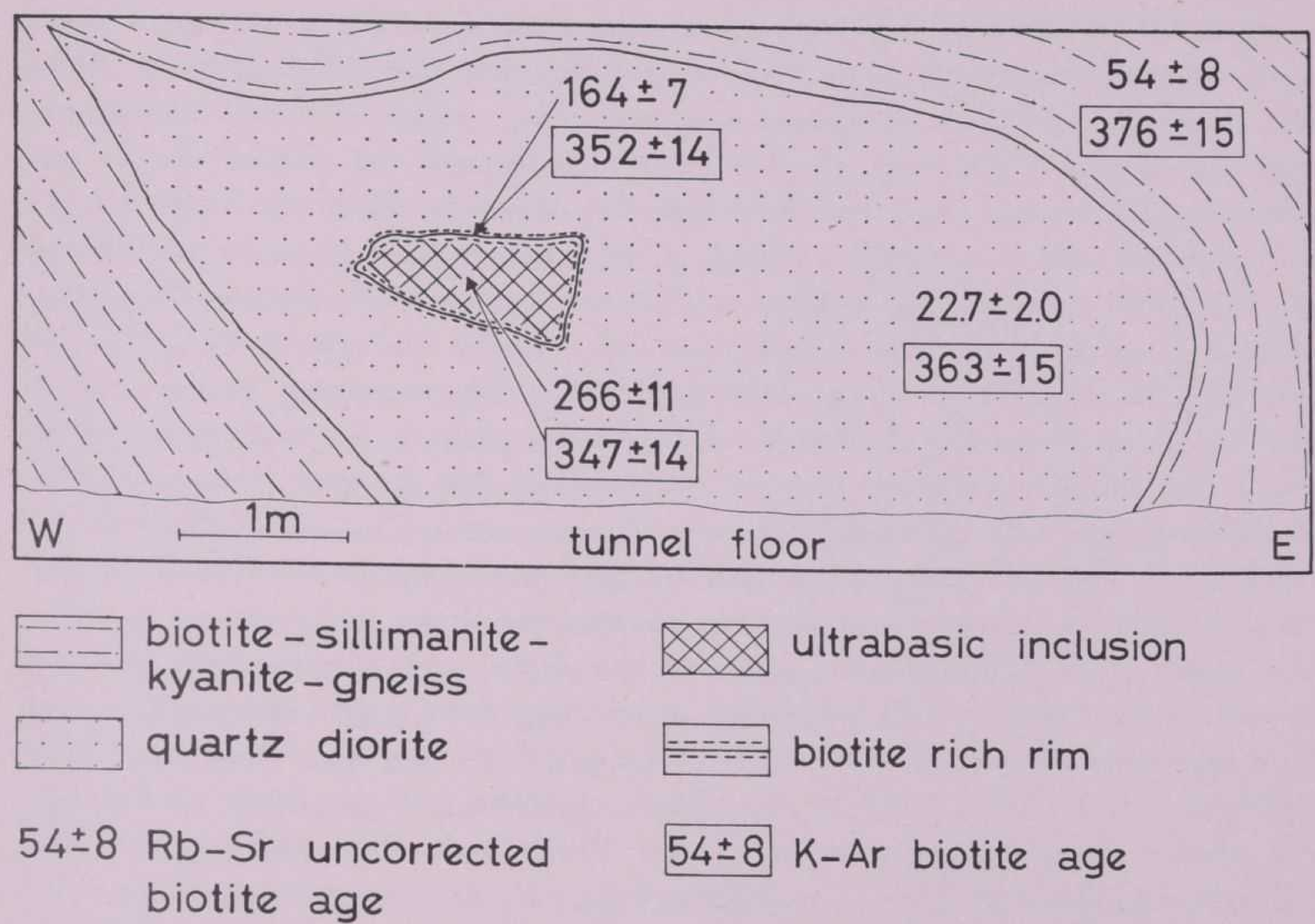

Fig. 1 - Rb-Sr and K-Ar Biotite Ages in Adjacent Rocks from the Chloritoid Zone of Alpine Metamorphism.

Arnold and Jäger, 1966, analysed by the Rb-Sr method four biotites of different rock types, collected within 8 meters of each other, again from the chloritoid zone of Alpine metamorphism. Fig. 1 gives a sketch of the outcrop, together with the Rb-Sr and K-Ar biotite ages. The genetic relationship between the analysed rocks is considered to be of pre-Alpine age: sample KAW 93, an ultrabasic inclusion of 1 m in diameter, surrounded by a thin layer of coarse grained biotite (KAW 126), both within a lense of quartz diorite of several meters in diameter (KAW 125), and all within the biotite-kyanite-sillimanite gneiss (KAW 124). The Rb-Sr biotite ages reported are quite different: 266 m.y. for the ultrabasic inclusion, 164 m.y. for the coarse grained biotite rim around it, 22.7 m.y. for the quartz diorite and 54 m.y. for the gneiss. Arnold and Jäger, 1966, give the following interpretation: in the ultrabasic inclusion, the pre-Alpine minerals could survive the Alpine metamorphism. The surrounding more acid rocks with their higher content of fluid phases show a higher grade of Alpine recrystallization. In all these rocks, the biotites are considered to be pre-Alpine in age; in the more acid rocks they show exsolution of titanium, inclusions of rutile and ilmenite. With the resetting of the Rb-Sr ages, the content of the titanium minerals in these biotites increases. This seems to indicate that the loss of rad. ^{87}Sr from the biotite is not caused by volume diffusion alone, but rather by a reconstitution of the cations of the octrahedral layer in the biotite.

We analysed the same biotites by the K-Ar method and obtained ages of 347 m.y., 352 m.y., 363 m.y. and 376 m.y. for the rocks from the ultrabasic inclusion to the gneiss. A small gradient in the K-Ar ages exists from the ultrabasic inclusion to the country rock, see Fig. 1. As 376 m.y. is older than the oldest phase of Hercynian metamorphism, these biotite ages must reflect the presence of a high partial pressure of radiogenic argon when the biotites cooled through the critical closure temperature. This kind of effect had been reported earlier by BREWER, 1969, for biotites collected over a much wider region in the Austrian Alps. If we assume that all the four biotites should have a K-Ar cooling age of 22 m.y., subtracting the amount of argon generated in the biotites in 22 m.y. leaves excess amounts of 112, 112, 104 and $111 \times 10^{-6} cm^3$ STP/gr argon. This similarity is not surprising, as the gradient of the K-Ar ages from the ultrabasic inclusion to the gneiss is not large and is partly due to the potassium variation. It is not unreasonable that biotites from such a restricted area may take up similar amounts of excess argon. This is not the only, but certainly the most plausible, explanation for these K-Ar ages. In every case, they are the result of excess argon, regardless what the meaningful age really should be.

In the whole chloritoid zone, *phengites* give Alpine ages, whereas muscovites can preserve at least part of their pre-Alpine argon; they seem to give intermediate ages. On a pegmatitic muscovite from the Tambo nappe, HANSON *et al.*, 1966, report even a Hercynian K-Ar age of 297 ± 15 m.y. The comparison with the Rb-Sr ages is difficult, phengites and muscovites having a lower Rb/Sr ratio than biotites, and thus higher error limits on the age results. All the K-Ar ages on muscovites and phengites are lower than the Rb-Sr ages calculated with normal common Sr, but in some cases (samples KAW 165, 281 and 378) higher than the Rb-Sr white mica ages calculated with the total rock. This age discrepancy can be explained by three different effects: some excess argon, incomplete Sr-homogenization with the « meaningful » white mica Rb-Sr age being in between « corrected » and the « uncorrected » age, and, as sample KAW 105 indicates, a third explanation is possible, namely the interpretation of intermediate Hercynian-Alpine muscovite ages. This last interpretation is possible only for muscovites and not for phengites; so far, we only know of Alpine phengites in the Alps. But we also could have intermediate ages between early and late Alpine (late Cretaceous and Tertiary) K-Ar phengite ages. On sample KAW 105, a pre-Alpine, somewhat lowered Hercynian Rb-Sr muscovite age of 238 ± 10 m.y. has been found. Thus, the K-Ar age of 58.8 ± 2.4 m.y. on the same muscovite is also best explained by assuming an intermediate age.

This shows once more how difficult it is to interpret the mica ages of the chloritoid zone. The muscovite of sample KAW 281 with the rather high K-Ar age of 43.2 ± 2.0 m.y. either has argon overpressure or it gives an intermediate age. The

K-Ar and Rb-Sr age discordance on the biotite from the same sample can be explained by excess argon or by incomplete Sr-homogenization.

GENERAL INTERPRETATION OF MICA AGES

Summarizing the earlier mentioned data and their explications, we can present the following model of interpretation of mica ages:

K-Ar mica ages from the staurolite zone (amphibolite facies) of Alpine metamorphism give young Tertiary ages, interpreted as cooling ages. K-Ar and Rb-Sr ages on biotites are concordant; the Rb - Sr muscovite (phengite) age is higher than the K - Ar white mica age and both exceed the biotite age of the same rock. In the outer staurolite zone a pre-metamorphic Rb-Sr white mica age might survive in resistant rocks. In the chloritoid zone (greenschist facies), biotite and muscovite may give Alpine, pre-Alpine or mixed Alpine-Hercynian ages. Phengite, a mineral formed during the Alpine metamorphism, always gives an Alpine age. For some of the biotites, a better degree of concordance between the Alpine K-Ar and Rb-Sr ages is achieved if we use the « uncorrected » Rb-Sr age, rather than using the « corrected » age, i.e. the age value of the biotite-total rock isochron. The implication of this is that the pre-Alpine in situ produced radiogenic ^{87}Sr was expelled during the Lepontine phase of Alpine metamorphism, but the « common » strontium of the biotite and the whole rock was not homogenized. Some of the biotites from the chloritoid zone must have incorporated an excess of radiogenic argon during the Alpine metamorphism, so that their K-Ar ages are too high. K-Ar ages on muscovites from the chloritoid zone may also be influenced by excess argon, but they could also be explained as intermediate pre-Alpine - Alpine ages, or early (Cretaceous) - late (Tertiary) Alpine ages.

The model of interpretation for the Rb-Sr ages on micas was developed earlier by JÄGER *et al.*, 1967, and JÄGER, 1973. In these papers, the position of the intermediate pre-Alpine to Alpine Rb-Sr ages on biotites has been compared to zones of Alpine metamorphic minerals. By assuming that the opening of the Rb-Sr system in biotite occurs at the same temperature as the closure during the cooling period, a blocking tempreature can be derived. This assumption may not be quite correct, as we find that the pattern of Rb-Sr biotite ages is different for the intermediate age zone and the area of completely rejuvenated cooling ages. The temperature of the opening of the Rb-Sr system in biotite is given by the maximum temperature of the Lepontine metamorphism (at 35 - 40 m.y. ago) in the intermediate age zone. The best estimate of this temperature in the zone of Alpine stilpnomelane is 300°C, therefore a blocking temperature of 300 ± 50°C has been postulated for the Rb-Sr system of biotites.

Muscovite systems react less sensitively to a later phase of metamorphism. The regional distribution of Rb-Sr ages on white micas (muscovite and phengite) indicates that there is no intermediate age zone. Unaffected pre-Alpine, Hercynian, muscovite ages are measured quite frequently in rocks with Alpine phengite. By comparing the transition from pre-Alpine to Alpine white mica ages, again with the occurrence of

Alpine metamorphic minerals, a temperature for the opening of the Rb-Sr system in white micas can be derived. The position of this transition is somewhat outside the staurolite-chloritoid boundary. From this fact, a temperature of 500 ± 50°C has been derived for the opening of the Rb-Sr system in white micas; in the earlier paper of Jäger *et al.*, 1967, a temperature interval of 400 - 500°C has been estimated. If we again assume that opening and closing of the Rb-Sr system in white micas occurs at the same temperature, the 500 ± 50°C can be interpreted as Rb-Sr blocking temperature in white micas.

It must be stated that the uncertainty of the proposed blocking temperatures is very difficult to evaluate. Our temperatures depend on the knowledge of the maximum temperature reached during the Lepontine metamorphism in a certain area. These temperatures are derived from experimental data and the precise mapping of metamorphic mineral boundaries. It might even be necessary in the future to change the proposed blocking temperatures if the equilibrium temperatures of metamorphic mineral reactions should be changed. At the moment, an uncertainty of ± 50°C might be a good estimate.

In contrast to biotite, muscovite and phengite can crystallize below their Rb-Sr blocking temperature. Therefore, in areas of lower grade of Alpine metamorphism, below 500°C, Rb-Sr white mica ages date the time of their formation. By this method the climax of the Lepontine phase of Alpine metamorphism has been dated to 35 - 40 m.y., see Hunziker, 1970 and 1974, and Jäger, 1973. In the regions of higher grade of metamorphism, above 500°C, Rb-Sr ages on muscovites and phengites date the cooling time to 500°C.

If we now compare the K-Ar to the Rb-Sr mica ages, we can derive blocking temperatures for the K-Ar systems in micas. As has been mentioned earlier, the Rb-Sr cooling ages agree with the K-Ar biotite ages. Thus, we assume that the blocking temperature for the K-Ar system in biotite also is 300 ± 50°C.

It is difficult to derive a blocking temperature for the K-Ar system in muscovite and phengite. We do not yet know the position of the K-Ar intermediate age zone of muscovite and phengite, i.e. the temperature at which K-Ar becomes an open system in white mica. We therefore try to relate this blocking temperature to those for Rb-Sr in biotite and white mica by comparing the different mica ages of the same rocks. Thus, the uncertainty of this blocking temperature is higher, because the errors in the K-Ar ages add to the uncertainty of the Rb-Sr blocking temperatures.

For a safe determination of the K-Ar white mica blocking temperature, an area of slow cooling within the staurolite zone should be selected. Further, the cooling rate between 500°C and 300°C should have been constant. By comparing the K-Ar age difference between muscovite and biotite to the Rb-Sr age difference, the blocking temperature for white mica has been calculated.

Fig. 2 shows the regional distribution of the K-Ar age differences between white micas and biotites. Only those ages are considered which can be interpreted as cooling ages. The plotted K-Ar age differences indicate the time span between the cooling from the muscovite to the biotite blocking temperature. This time span is short and

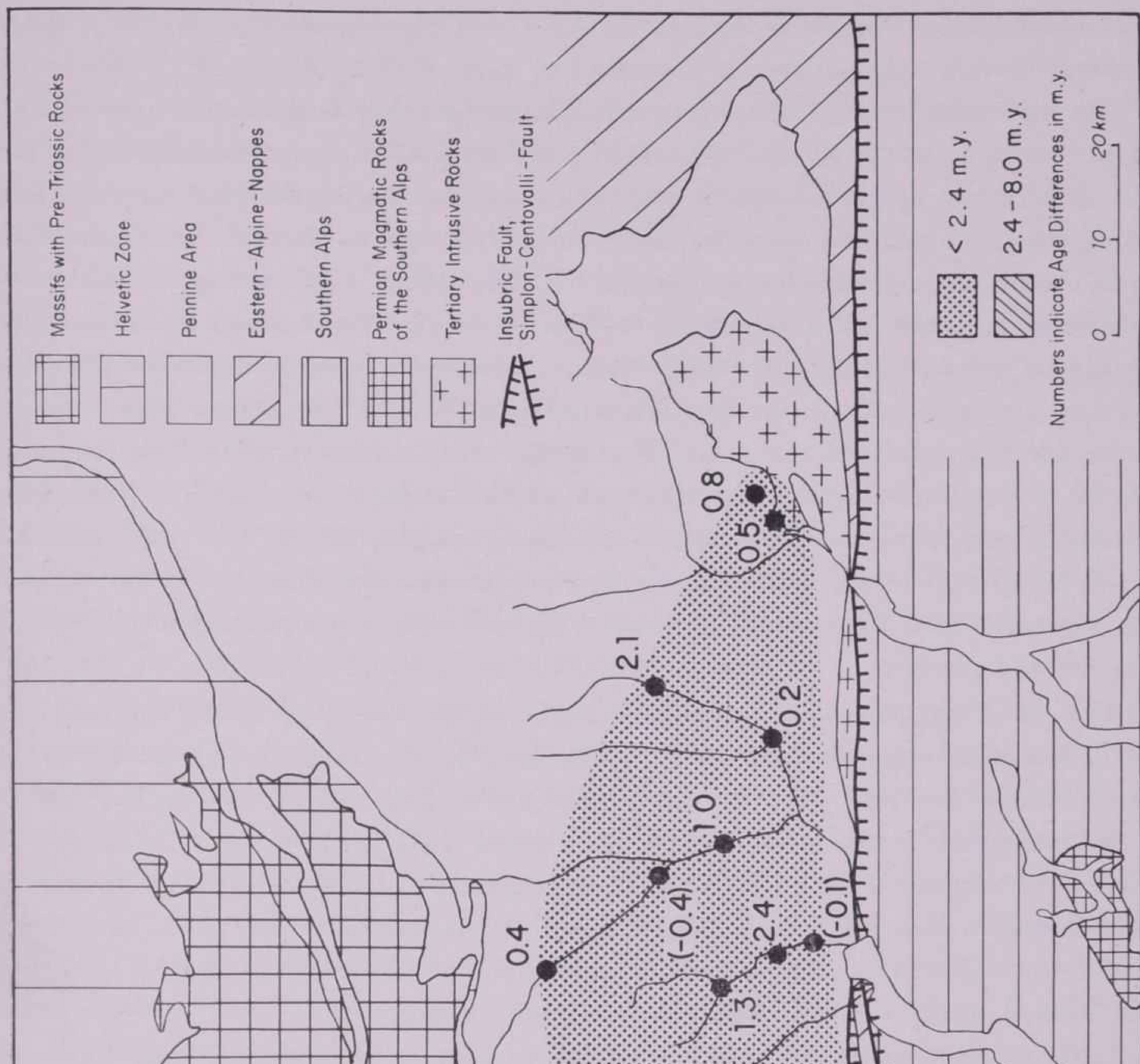

Fig. 2 K-Ar Age Differences between Coexisting Muscovite (Phengite) and Biotite

rather homogeneous from the Bergell to the Val Antigorio, around 1.1 m.y. To the northwest of the Simplon area it increases to more than 7 m.y.

For the evaluation of the white mica K-Ar blocking temperature, the Simplon area with samples no. KAW 159, 160, 161, 358 and 372 seems favorable: the K-Ar white mica-biotite age differences are higher than the ones to the east, and the grade of Alpine metamorphism (staurolite zone) is high enough, so that we can interpret the ages as cooling ages. Except for sample KAW 372, which is situated 10 km to the southeast of the other samples, all the biotite Rb-Sr ages (calculated as biotite - total rock ages) agree within the error limit. Again, except for sample KAW 372, all the K-Ar ages also agree. The mica ages for sample KAW 372 are about 2 m.y. higher, but the age differences are the same. The mean white mica - biotite K-Ar age difference of these samples is 2.7 m.y. Because of the rather low Rb/Sr- ratios Rb-Sr white mica ages could be determined only from samples KAW 160, 358 and 372. The Rb-Sr age difference between the white micas and the biotites is less precise, being around 7 m.y. This would indicate a K-Ar blocking temperature of 380°C for muscovite and phengite.

This blocking temperature seems too high for the Ticino area, i.e. the area from the Val Antigorio (sample KAW 201) in the west to the Bergell region in the east (samples KAW 552 and 553). In this region the cooling seems to be rather uniform and fast, compared to tbe Simplon area. The mean K-Ar white mica - biotite age difference of 14 samples is 1.1 m.y. The K-Ar age difference of sample KAW 4, Brione, the standard sample (see Fig. 2 and Tables I and II), is well determined, it is 1.3 m.y. Brione is located in the center of the Ticino area, on the map of Fig. 2 it can be easily located, being the only age difference of 1.3 m.y.

Unfortunately, we do not have precise Rb-Sr ages on muscovites from this area. We have to compare the K-Ar age difference between muscovite and biotite to the general cooling rate, derived from other evidence. If we assume a blocking temperature of 380°C for the muscovite K-Ar ages, the small muscovite-biotite age difference of 1.1 or 1.3 m.y. would give a very fast cooling rate of 60 to 70°C/per million years. This cooling rate is too high when compared to the cooling rate from 300°C to the present day temperature, which is only 18°C/m.y., i.e. for the time from 17 m.y. ago to the present. Another estimate of cooling rates may be derived from U-Pb ages on monazites, published by Köppel and Grünenfelder, 1975.

These authors give a U-Pb age of 22.8 m.y. for a monazite from a sample just north of Brione/Verzasca, near to our standard mica sample. Köppel and Grünenfelder, 1975, interpret these ages as formation ages, dating the climax of metamorphism. If we accept their interpretation and assume a maximum possible temperature of 650°C for the Alpine metamorphism near Brione, Verzasca, a mean cooling rate of 28°C/m.y. from 23 m.y. ago to the present would result. If we consider the cooling rate between 650 and 300°C, from 23 to 17 m.y. ago, we would find a high cooling rate of 58°C/m.y., again following the interpretation of the monazite U-Pb ages by Köppel and Grünenfelder, 1975. According to Hunziker and Jäger, in preparation, U-Pb ages on monazites should be interpreted as cooling ages with a maximum blocking temperature of 530°C. If we accept this blocking temperature, the cooling rate from 23 m.y. to the present would be 23°C/m.y.; from 23 to 17 m.y. ago, from 530 to 300°C, it would be 38°C/m.y. All these mean cooling rates are lower than the one derived by means of a K-Ar blocking temperature of 380°C for muscovite. Thus, this blocking temperature should be lower; the temperature difference between the K-Ar blocking temperatures for muscovite and biotite cannot be higher than 50°C, which would mean a blocking temperature of 350°C for muscovite. With 1.1 to 1.3 m.y. time for the cooling from 350 to 300°C, a reasonable cooling rate of 38 to 45°C/m.y. would result. We consider the Ticino area more reliable than the Simplon region for the evaluation of the blocking temperatures, as its uplift rate seems to have been constant relative to the uplift rate of the Simplon, see Wagner *et al.*, in press.

Two points we would like to emphasize in connection with the interpretation of mica ages: we are not certain whether muscovite and phengite really have the same blocking temperatures for K-Ar and Rb-Sr dating. There may be small differences between these two minerals which we have not yet been able to detect. Secondly, as mentioned above, we found this interpretation of Rb-Sr and K-Ar mica ages to be valid only for the Lepontine phase of metamorphism.

In the area of late Cretaceous metamorphism, which is adjacent to the above discussed Lepontine region, a different pattern of mica age discordance is found. As compared to the Lepontine metamorphism, the Cretaceous phase is characterized by a lower geothermal gradient, it represents a high-pressure type of metamorphism. In contrast to the results from the Lepontine area, the regional mica age distribution is less regular. Quite frequently, the K-Ar muscovite or phengite ages are higher than the Rb-Sr ages. Furthermore, low temperature alterations in connection with fluid phases again give a different mica age pattern, different from those of the Lepontine and the high-pressure phase.

We assume that the important parameters which permit the above proposed interpretation of mica ages in the Lepontine metamorphic phase are: medium geothermal gradients around 30°C/km, a rather small content of fluid phases and a slow undisturbed cooling following the climax of temperature.

The interpretation of mica ages according to the Lepontine model is valid only for metamorphic phases with similar physical and chemical parameters.

INTERPRETATION OF REGIONAL VARIATIONS OF K-Ar AGES

Plate I shows the regional distribution of K-Ar biotite ages. South of the Insubric line we find only pre-Alpine ages, whereas north of this line we have young Tertiary ages. These young biotite ages vary gradually from 23 m.y. in the Bergell region to a low of 11 m.y. in the Simplon area. Westward from the Simplon and north of the Simplon-Centovalli fault, the biotite ages again increase to 14 m.y. This K-Ar age pattern is identical to the Rb-Sr age pattern (Jäger and Hunziker, 1969), except for the region northwest of the Simplon, where the Rb-Sr biotite ages remain at 11 m.y. and the K-Ar ages increase to 14 m.y. The possible reason for this discordance has been discussed in the previous section. Across the Simplon-Centovalli fault we have a sharp discontinuity from 11 m.y. in the north to greater than 20 m.y. just south of the fault. HUNZIKER, 1970, has already discussed the history of this fault from his Rb-Sr data. It is interesting that the fission track data on apatites (WAGNER and REIMER, 1972) also show an age discontinuity for the same samples. The fission track ages for samples KAW 159, 160 and 161 average 2.7 m.y. while that of KAW 370 is 6.2 m.y. This must mean that the fault was still in action at least as recently as 2.7 m.y. ago.

Plate II gives the regional distribution of the K-Ar muscovite (phengite) ages showing an age pattern similar to the K-Ar biotite age pattern. The ages decrease from 24 m.y. in the Bergell region (samples KAW 552 and 553) to a low of 13.8 m.y. in the Simplon. Proceeding westward from the Simplon and north of the Simplon-Centovalli fault, the ages increase to greater than 18 m.y. Again there is a hiatus in age from 14.8 m.y. to greater than 20 m.y. across the Simplon-Centovalli fault.

Additional geological information may be obtained from the K-Ar muscovite data. Firstly, the pegmatites from the Val Verzasca (samples B 2, B 9 and B 11) are post metamorphic. They cut the well oriented Verzasca gneiss, but the large beryl and muscovite crystals in the pegmatites show no preferred orientation. The pegmatitic and rock muscovite K-Ar ages are the same, which means that the pegmatites must have intruded into the gneisses in the time interval between the metamorphic temperature climax and the cooling time to 350°C. Secondly, there was a doming in the Val Leventina after the rocks in the general region had cooled below 350°C. The muscovites in Val Leventina (samples KAW 137, 138 and 140) are about 2 m.y. younger than those on either side of it, which means that these rocks from the Val Leventina passed through the 350°C geotherm later. The doming of the Val Leventina is superimposed on the general uplift. The updoming of the Leventina is also shown by the U-Pb ages on monazites by KÖPPEL and GRÜNENFELDER, 1975. The monazite ages from the Leventina are also about 2 m.y. younger than the ones east and west of the Leventina. This shows quite drastically that the U-Pb monazite age cannot date the climax of the metamorphism with the crystallization of the monazite. Why should the climax of the metamorphic temperature be reached earlier in rocks of higher tectonic position? But it is easy to understand that rocks of a higher tectonic position could cool earlier than the deeper ones.

Fig. 2 gives the regional distribution of the K-Ar age differences between muscovite (phengite) and biotite. We find also a uniform and gradually changing age difference pattern. From the Bergell to Val Antigorio, the age difference is less than 2.4 m.y.; from Val Antigorio to the Simplon, just north of the Simplon-Centovalli fault, the age difference increases to 4 m.y., and northwest to the Nanztal the K-Ar age difference between coexisting white mica and biotite rises to 8 m.y. Hence, not only do we have rocks passing through the temperature interval of 350°C to 300°C at different times, but also at different rates.

This shows that those rocks which have the oldest biotite cooling ages passed quickest through the temperature interval of 350 to 300°C. This must mean that the more recent uplift (less than 10 m.y.) is vastly different from that which occurred when the rocks exposed today passed through the 350 to 300°C temperature interval.

In fact, the rocks from the Simplon region and the area northwest of the Simplon must have risen more quickly in recent time than those southwest and east of the Simplon. The implication is that uplift rates are not constant and may both decrease and increase with time. A more detailed analysis of the uplift and cooling history of the Central Alps will be given by WAGNER *et al.*, in press.

CONCLUSIONS

The following are the main conclusions from the present investigation:

1. Within the staurolite zone (amphibolite facies) of Alpine metamorphism, all the K-Ar ages on biotites and muscovites are Tertiary and less than 38 ± 2 m.y., the time of the climax of the last phase of Alpine metamorphism, the so-called Lepontine phase. These young ages are interpreted as cooling ages.

Both the biotite and muscovite (phengite) K-Ar ages show a regional distribution of ages, similar to the Rb-Sr biotite age pattern. If the cooling has been sufficiently slow to allow coexisting mica pairs to fall through their critical closure temperatures at different and now measurable times, the following age sequence is observed:

Rb-Sr (musc., pheng.) > K-Ar (musc., pheng.) > Rb-Sr (biot.) = K-Ar (biot.)

The concordance of the Rb-Sr and K-Ar biotite ages suggests that the closure temperature for radiogenic argon and strontium is the same. A closure temperature for argon loss from muscovite and phengite of 350°C is derived from Rb-Sr and K-Ar age data, including also some U-Pb monazite data (KÖPPEL and GRÜNENFELDER, 1975) from the Ticino area. Using the data from the Simplon region would lead to a white mica K-Ar blocking temperature of 380°C, which we consider to be less reliable because of drastically changing uplift rates in this area.

In resistant rocks from the lower grade region of the staurolite zone, pre-metamorphic Rb-Sr muscovite ages may survive.

2. In the chloritoid zone (greenschist facies), biotites and muscovites may give Alpine, pre-Alpine or mixed Alpine-Hercynian K-Ar ages. For some of the young biotite cooling ages, concordance of Rb-Sr and K-Ar ages is achieved if we use a normal $^{87}Sr/^{86}Sr$ ratio, or the initial $^{87}Sr/^{86}Sr$ ratio of the pre-Alpine total rock isochron to correct for the non-radiogenic strontium. Discordant Rb-Sr and K-Ar biotite ages result from calculating the Rb-Sr biotite age with the total rock, the discordance giving an older K-Ar age. This implies that, in the chloritoid zone, some of the biotites lost their radiogenic ^{87}Sr component during the Alpine metamorphism, but did not exchange their « common » strontium with the total rock reservoir.

In the chloritoid zone, the correct interpretation of K-Ar ages is made more difficult by that fact that higher ages might also be caused by excess argon and by incomplete rejuvenation during the metamorphism.

3. K-Ar cooling ages are insensitive to grain size; both rock muscovite and pegmatitic muscovite, as well as rock biotite and pegmatitic biotite, locally giving concordant ages.

Table 3 - Interpretation of Mica Age Results in the Lepontine Metamorphic Zones

BLOCK CAPITALS - INTERPRETATION CLEAR
standard letters - interpretation problematic

Methods/ Minerals	Staurolite Zone Amphibolite Facies > 540°C	Chloritoid Zone Greenschist Facies < 540°C
K - Ar biotite	COOLING AGE TO 300 ± 50°C,	cooling age to 300 ± 50°C, possibility of excess argon and inherited argon (intermediate ages)
Rb - Sr biotite	COOLING AGE TO 300 ± 50°C SR HOMOGENIZATION WITHIN TOTAL ROCK SAMPLE, biotite has to be calculated as biotite - total rock isochron = « corrected age »	cooling age to 300 ± 50°C, incomplete Sr homogenization in total rock sample, preferential loss of radiogenic strontium possible, in resistant rocks pre-metamorphic or intermediate ages can be retained, no certain age solution
K - Ar muscovite phengite	COOLING AGE TO ABOUT 350°C	cooling age to about 350°C, excess argon possible, unaffected pre-Alpine muscovite can retain its pre-Alpine age
Rb - Sr muscovite phengite	COOLING TO 500 ± 50°C especially in muscovite, large errors expected due to low Rb/Sr ratios, in resistant rocks pre-metamorphic ages may survive in the lower part of the staurolite zone	pre-Alpine muscovites can retain their pre-Alpine ages ALPINE MUSCOVITE AND PHENGITE DEFINE FORMATION AGES in rocks with two white mica generations mixed ages expected

IN THE STILPNOMELANE ZONE TRANSITION FROM PRE-ALPINE TO ALPINE BIOTITE AGES
OUTSIDE THE STILPNOMELANE ZONE ALL THE PRE-ALPINE MICAS RETAIN THEIR AGES

4. The K-Ar ages of pegmatitic and rock muscovites from Val Verzasca are concordant, indicating that the post-metamorphic pegmatites intruded before the country rocks had cooled to about 350°C.

5. A doming in the Val Leventina, superimposed on the general uplift, is indicated by the K-Ar muscovite and the U-Pb monazite ages. Thus, if K-Ar on muscovites dates a cooling stage, U-Pb ages on monazites also must represent cooling ages.

6. There is a regional variation in the age difference between coexisting muscovite (phengite) and biotite. This means that the rocks cooled at different rates in the temperature interval between 350 and 300°C, this cooling rate being much smaller for the Simplon than for the Ticino area.

Table 3 summarizes the interpretation of K-Ar and Rb-Sr mica ages in the different zones of the Lepontine Alpine metamorphism.

ABSTRACT

Ninety new K-Ar ages of minerals from the Central Alps are presented. The majority have been made on coexisting mica pairs already analysed by the Rb-Sr method. Other analyses include single pegmatitic and rock micas. From five rocks the potassium feldspar and plagioclase were analysed in addition to the mica pair.

Some of the micas from the chloritoid zone and all of the micas from the staurolite to kyanite-sillimanite zone yield young Tertiary K-Ar ages, interpreted as cooling ages. The K-Ar cooling ages give a geographic pattern for both biotites and muscovites (phengites) similar to the Rb-Sr biotite age pattern. The potassium feldspars show no systematic pattern, in some cases they are lower than the biotite age, in other cases even higher than the phengite ages.

If the rate of cooling has been sufficiently slow to allow the micas to close to daughter nuclide loss at different, and today measurable, times the following age pattern is observed within a given rock:

Rb-Sr (musc., pheng.) $>$ K-Ar (musc., pheng.) $>$ Rb-Sr (biot.) $=$ K-Ar (biot.)

Within the zone of Alpine staurolite, where all the mica ages represent cooling ages, the difference between the K-Ar muscovite (phengite) age and the coexisting biotite age varies regionally; the age difference being on the average 1.1 m.y. from the Bergell intrusion to Val Antigorio; 2.4 - 4 m.y. from Val Antigorio to the Simplon; and 4 - 8 m.y. northwest of the Simplon, north of the Simplon-Centovalli fault. This is interpreted as giving the regional variation of uplift rates as the rocks passed through the temperature interval between the closure temperature for radiogenic argon loss from muscovite (phengite) to biotite.

The Simplon area must have been uplifted and cooled slowly to 300°C, followed by a drastic increase of the uplift rate as indicated by the young Rb-Sr and K-Ar biotite ages. As has been demonstrated already with Rb-Sr biotite ages by Jäger *et al.*, 1967, and Jäger and Hunziker, 1969, the late regional cooling pattern cuts the main tectonic lines, it is offset only by the Simplon-Centovalli fault. In the earlier stages of cooling, the updoming of the deep tectonic units Verampio and Leventina is superimposed on the regional uplift. This is shown by younger Rb-Sr and K-Ar ages on muscovite from the tectonically deeper Verampio granite gneiss and younger K-Ar ages on the muscovites from the Leventina gneisses compared to white mica ages of the neighbouring rocks with higher tectonic position.

ZUSAMMENFASSUNG

In dieser Arbeit werden neunzig neue K-Ar Altersbestimmungen aus den Zentralalpen publiziert. Es handelt sich dabei vorwiegend um Messungen an Glimmerpaaren — Hellglimmern und Biotiten — aus Gneisen, die in verschiedenem Ausmass von der tertiären Lepontin-Metamorphose geprägt wurden. Dazu kommen noch Messungen an Biotiten aus dem Bereich der Mischalterszone und Pegmatit-Glimmern; an fünf Proben wurden neben den Glimmerpaaren auch Kalifeldspat und Plagioklas datiert.

An Hand der regionalen Verteilung der K-Ar Alterswerte und aus dem Vergleich mit den Rb-Sr Daten konnte ein Modell der Interpretation von K-Ar und Rb-Sr Glimmeraltern entwickelt werden. Dieses Schema der Interpretation von Altersdaten ist nur für den Typus der Lepontin-Metamorphose gültig, d.h. für eine Metamorphose mit mittlerem Thermogradient und nur geringer Beteiligung von fluiden Phasen.

Im Bereich der Amphibolitfazies wurden für die Biotite idente K-Ar und Rb-Sr Alterswerte gefunden, ident auch in der regionalen Verteilung. All diese Daten können als Abkühlalter auf 300 ± 50°C interpretiert werden. Die Interpretation der Biotit-Alterswerte in der Zone von alpinem Chloritoid, der Zone der Grünschieferfazies, macht Schwierigkeiten. Ueberschuss-Argon, nur teilweise Verjüngung der voralpinen Biotite und inkompletter Strontium-Austausch innerhalb eines Gesteins machen oft eine sichere Interpretation unmöglich.

Das Rb-Sr System in Hellglimmern, Muskowit und Phengit, ist relativ stabil, es schliesst schon bei Temperaturen von 500 ± 50°C. Nur in Gesteinen, die bei der Metamorphose wesentlich über 500°C aufgeheizt wurden, d.h. Gesteine aus der Amphibolitfazies mit alpinem Staurolith, datieren die Hellglimmer mit der Rb-Sr Methode Abkühlalter. In Zonen niederer Metamorphose bestimmt man mit dieser Methode an neugebildeten Hellglimmern direkt das Alter der Glimmerbildung, d.h. wohl den progressiven Ast des Temperatur-Maximums. So fanden wir am Aussenrand der Lepontin-Metamorphose, d.h. im nieder gradigen Bereich, stets Rb-Sr Hellglimmeralter von 35 - 40 Millionen Jahren. Damit wurde der Climax der Lepontin-Metamorphose bestimmt, was mit den Ergebnissen aus der Geologie, die diese Metamorphose an die Grenze Eozän-Oligozan legt, gut übereinstimmt.

Im Bereich der Amphibolitfazies mit Temperaturen über 500°C datieren alle Glimmer mit beiden Methoden Abkühlalter. Hier ergibt sich für die Glimmerpaare eines Gesteins ohne Ausnahme die folgende Alters-Relation:

$$\text{Rb-Sr}_{(\text{Musk., Pheng.})} > \text{K-Ar}_{(\text{Musk., Pheng.})} > \text{K-Ar}_{(\text{Biot.})} = \text{Rb-Sr}_{(\text{Biot.})}$$

Die K-Ar Alter an Hellglimmern sind also stets niederer als die Rb-Sr-, aber höher als die Biotit-Alter. Vergleicht man im Tessin, wo man am ehesten mit einer zeitlich konstanten Abkühlung rechnen kann, die K-Ar Hellglimmeralter mit den anderen Alterswerten, so kommt man für das K-Ar System in Muskowit und Phengit zu einer Schliessungstemperatur von 350°C, mit einem Fehler von mind. ± 50°C.

Der Vergleich mit den Rb-Sr Altern an Hellglimmern ist schwierig, da vor allem der Muskowit mit seinen im allgemeinen recht niederen Rb/Sr- Verhältnissen mit der Rb-Sr Methode nur schlecht, d.h. mit grossem Fehler, zu datieren ist. Die K-Ar Methode hat diesen Nachteil nicht, Hellglimmer und Biotit sind im alpinen Bereich mit gleicher hoher Genauigkeit datierbar. Die Alters-Differenzen zwischen den K-Ar Altern von Hellglimmern und Biotiten sind damit gut erfassbar, sie geben die Zeitdauer für die Abkühlung von 350 auf 300°C. Diese Altersdifferenz ist konstant für den Tessin vom Bergell bis zum Val Antigorio, sie beträgt hier im Durchscnitt 1.1 Millionen Jahre. Gegen den Simplon zu steigt sie auf 4 und weiter nordwestlich zum Nanztal bis auf 8 Millionen Jahre an. Die Abkühlung auf 300°C war also hier, im Gebiet Simplon-Nanztal, sehr langsam. Da man ausgerechnet hier die jüngsten Biotitalter findet, muss die Abkühl- und damit die Hebungsgeschwindigkeit später sehr stark angestiegen sein.

Die regionale Verteilung der K-Ar Alter, d.h. Zonen gleicher Alterswerte, schneidet alle tektonischen Grenzen, mit der Ausnahme der insubrischen Linie, die die voralpinen von den alpinen Altern trennt, und der Simplon-Centovalli-Störung, an der die K-Ar Abkühlalter sprunghaft ändern. Dieselben Beobachtungen waren früher mit Rb-Sr Altern an Biotiten gemacht worden, siehe JÄGER *et al.*, 1967, und HUNZIKER, 1970. Generell lässt sich zur Abkühlgeschichte sagen, dass im Frühstadium der Abkühlung die Aufwölbung von Verampio und der Leventina gegen die benachbarten tektonisch höheren Einheiten hervortritt. Dies lässt sich im Fall von Verampio mit Rb-Sr Altern an Hellglimmern und in der Leventina mit U-Pb Altern an Monaziten, siehe KÖPPEL und GRÜNENFELDER, 1975, und K-Ar Altern an Hellglimmern zeigen. Alterswerte, die ein späteres Stadium der Abkühlung datieren, wie die K-Ar und Rb-Sr Alter an Biotiten, zeigen diese Aufwölbung nicht mehr. Im späteren Abkühlstadium dominiert eine regionale Hebung, die Aufwölbung zur Tessiner Kulmination ist weitgehend abeschlossen.

Zur Interpretation der Glimmeralter mag noch bemerkt werden, dass Abkühlalter stets unabhängig sind vom Korndurchmesser des Glimmers. So liefern die grobkörnigen Pegmatit-Muskowite und die feinkörnigen Muskowite der benachbarten Tessiner Gneise idente K-Ar Alterswerte. Dies bedeutet aber auch, dass die sicher post-metamorphen Pegmatite des Verzasca-Tales gebildet wurden, als die Temperatur der Nebengesteine noch höher war als 350°C.

RIASSUNTO

Vengono qui pubblicate novanta nuove età K-Ar di minerali delle Alpi Centrali. La maggioranza fu stabilita su coppie di miche coesistenti, già analizzate col metodo Rb-Sr. Altre analisi riguardano singole miche di origine pegmatica o ricavate da rocce. Di cinque rocce vennero analizzate, oltre alle coppie di miche, anche il feldispato potassico ed il plagioclasio.

Alcune miche della zona a cloritoide e tutte le miche provenienti dalla zona a staurolite fino alla zona a cianite-sillimanite danno età K-Ar del Terziario recente, interpretate come età di raffreddamento. Le età K-Ar di raffreddamento indicano, sia per le biotiti che per le muscoviti (fengiti), una distribuzione geografica simile a quella ottenuta per le età Rb-Sr della biotite. I feldispati potassici non mostrano alcuna distribuzione sistematica; in alcuni casi essi offrono età più basse di quelle della biotite, in altri casi età persino più alte della fengite.

Se il tasso di raffreddamento è stato sufficientemente lento da permettere alle miche di concludere la perdita del nuclide figlio in tempi differenti ed oggi misurabili, si osserva in una data roccia il seguente modello di età:

$$\text{Rb-Sr(musc., feng.)} > \text{K-Ar(musc., feng.)} > \text{Rb-Sr(biot.)} = \text{K-Ar(biot.)}$$

Nella zona della staurolite alpina, dove tutte le età della mica rappresentano età di raffreddamento, la differenza tra l'età K-Ar della muscovite (fengite) e l'età della biotite coesistente varia regionalmente; tale differenza di età si aggira in media su 1.1 m.a. dal massiccio intrusivo di Bregaglia alla Val Antigorio; su 2.4 - 4 m.a. dalla Val Antigorio al Sempione; e su 4 - 8 m.a. a nordovest del Sempione, a settentrione della faglia Centovalli-Sempione. Si ritiene che questo fatto esprima la variazione regionale dei tassi di sollevamento quando la roccia passava attraverso l'intervallo di temperatura compreso fra le temperature di chiusura per la perdita dell'argon radiogenico della muscovite (fengite) e della biotite.

L'area del Sempione deve esser stata sollevata e raffreddata lentamente fino a 300°C; seguì un drastico incremento del tasso di sollevamento, com'è indicato dalle età recenti Rb-Sr e K-Ar della biotite. Come venne già dimostrato con le età Rb-Sr della biotite da JÄGER *et al.*, 1967, e da JÄGER e HUNZIKER, 1969, la distribuzione del raffreddamento regionale tardivo taglia le principali linee tettoniche ed è rigettato soltanto dalla faglia del Sempione-Centovalli. Nei primi stadi di raffreddamento, il sollevarsi a duomo delle unità tettoniche profonde di Verampio e di Leventina si è sovrimposto all'innalzamento regionale. Ciò è dimostrato dalle età più recenti Rb-Sr e K-Ar della muscovite nello gneiss granitico tettonicamente più profondo di Verampio, nonchè dalle età più giovani K-Ar della muscovite negli gneiss di Leventina, paragonate alle età della mica bianca delle rocce vicine situate in posizione tettonica più alta.

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