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BOCQUET, Jacqueline, *et al.*

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Reference

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K—Ar and Rb—Sr Dating of Blue Amphiboles, Micas, and Associated Minerals from the Western Alps

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Abstract. The results of 63 new radiometric K—Ar and Rb—Sr measurements on metamorphic minerals from the internal units of the Western Alps show Hercynian, Permian, as well as three Alpine age groups. The first of the Alpine ages cover the period between 78 and 100 m.y. and refer to high pressure parageneses. The second group comprises K—Ar 39 to 50 m.y. ages; these values are affected by some inherited argon, as indicated by Rb—Sr measurements which point to 35—36$\pm$4—5 m.y., i.e. similar to the culmination of the Lepontine crystallization. The final group includes 15 to 30 m.y. ages. It is not yet clear which geologic processes have led to this isotope re-equilibration. Large amounts of inherited argon have been found in Alpine metamorphic minerals of the basement rocks.

Introduction

The Western Alps comprise the area from Ligury in the south to the Valais region in the north, where they are separated from the Central Alps by the Simplon-Centovalli fault line. The general structure (see Fig. 1), paleogeography and tectonic evolution of the Western Alps have been outlined in particular by Trümpy (1960, 1973), and by Debelmas and Lemoine (1970).

Sodic amphiboles are characteristic minerals of the Alpine metamorphism in the Western Alps. Beyond the thermal culmination of the Central Alps (Lepontine culmination), blue amphiboles reappear in the Engadine and in the Tauern window (Oxburgh *et al.*, 1966; Oberhauser, 1968; Jäger, 1973).

The data presented here concern mainly the French Western Alps. The Alpine metamorphism in the Western Alps has been regionally studied by various authors. Distribution maps of Alpine metamorphic minerals, general discussion and references are given by: van der Plas (1959), Bearth (1962, 1966), Niggli and Niggli (1965), Bortolami and Dal Piaz (1970), Bocquet (1971), Dal Piaz (1971), von Raumer (1971), Dal Piaz *et al.* (1972), Saliot (1973), Bocquet *et al.* (in press).

The general scheme that arises for the metamorphism in the Western Alps is the following (Fig. 1):

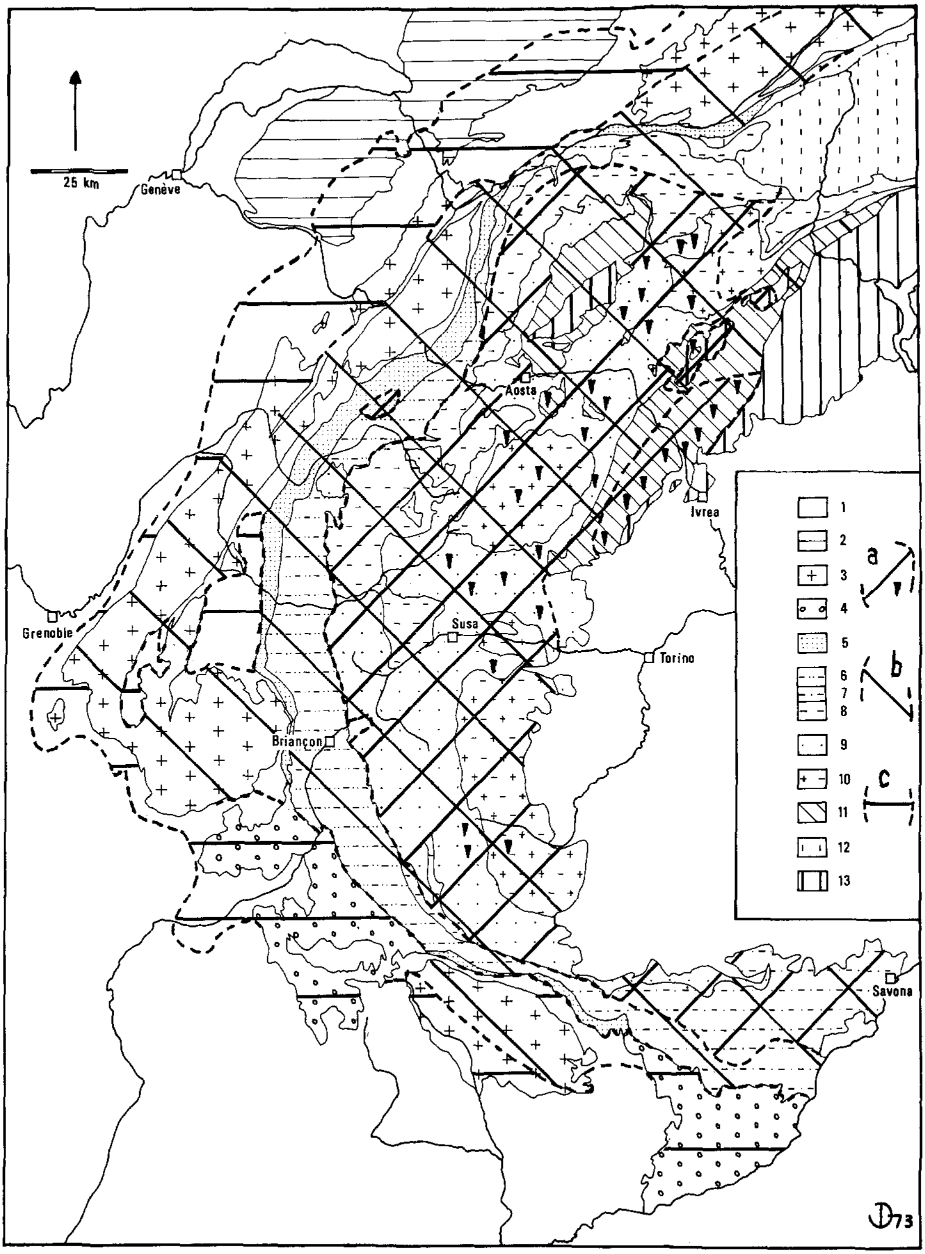

Fig. 1. Structural units of the Western Alps: *1* Dauphiné-Helvetic sedimentary cover; *2* Prealps nappes; *3* Dauphiné-Helvetic crystalline basement; *4* Embrunais-Ubaye and Ligury flysch, including Helminthoid flysch; *5* Subbriançonnais zone, Valais zone and Versoyen; *6* outer Briançonnais-Bernhard zone ("zone houillère" and cover); *7* Briançon-Bernhard zone in the Ligurian Alps, undifferentiated; *8* inner Briançonnais-Bernhard zone (mainly crystalline basement); *9* Piemont "Schistes lustrés" and ophiolites, Lanzo massif; *10* Mt Rosa—Gran Paradiso—Dora-Maira unit; *11* lower Austroalpine units: Sesia-Lanzo zone, Arolla nappe and klippen: Mt Emilius, Rafray-Glacier, Pillonet; *12* lower Penninic nappes; *13* Southern Alps, including Ivrea zone, and related klippen and nappes: 2nd Diorito-kinzigitic zone and Valpelline nappe; Canavese zone. As overprint mineral parageneses groups of the different phases of Alpine metamorphism. *a* eclogitic and glaucophanic parageneses; ▼ eclogites; *b* greenschist facies parageneses ± lawsonite, pumpellyite, prehnite, *c* zeolite facies parageneses and anchizone

a) Eclogitic and glaucophanic parageneses ± (jadeite + quartz) ± kyanite ± lawsonite ± paragonite ± chloritoid ± phengite ± chlorite occur in part of the Sesia-Lanzo zone, the Piemont zone (including the Piemont crystalline basement), and part of the Briançon-Bernhard unit. Jadeite-rich pyroxenes are until now only known in the Sesia zone, in the SW part of the French-Italian Alps, from the Acceglio zone in the south up to the Vanoise and the Gran Paradiso massifs in the north, and in the Versoyen.

b) Greenschist facies parageneses, with chlorite + albite ± blue-green amphibole ± actinolite ± green and brown biotite overprint the eclogitic and glaucophanic parageneses, with exception of the SE part of the Sesia-Lanzo zone. Towards the west the greenschist parageneses are overlapping the high-pressure mineral field and reach the region of:

c) Very low grade metamorphic parageneses: laumontite facies, pumpellyite—prehnite facies, pumpellyite—actinolite facies. The distribution of the zeolite facies zone on Fig. 1 follows the occurrence of zeolites, as well as that of the anchizone as defined by the crystallinity of illite. Zeolites, pumpellyite, prehnite, and greenschist minerals occur in the "Taveyannaz" and "Champsaur sandstones" an Oligocene volcano-detrital formation, lying west of the Mont Blanc and south of the Pelvoux massif.

The Alpine age of the eclogitic and glaucophanic metamorphism of the Sesia zone has for a long time been disputed, but has recently been established by Scheuring *et al.* (1974) and Dal Piaz *et al.* (1972, 1973).

Different generations of glaucophane s.l., lawsonite, chloritoid, pumpellyite ± paragonite strongly complicate the evaluation of a chronological picture based purely on petrographic evidence.

Between the Hercynian and the Alpine metamorphism a Permian event may have taken place, the existence of which has so far been documented only in the Mt Rosa massif (Hunziker, 1970).

Until now geochronological evidence concerning the Alpine metamorphism in the Western Alps is provided by geological, paleontological, petrographic and radiometric data on micas, amphiboles and feldspars.

1. From structural data obtained in and near the Dora-Maira massif a Cretaceous phase of deformation and metamorphism has been inferred by Vialon (1966). Sedimentary unconformity of the Albian-Upper Cretaceous flysch lead Haccard *et al.* (1972) to postulate a Middle Cretaceous, probably Early Albian, phase of deformation and metamorphism.

2. Upper Cretaceous fossils (Globotruncana: Raguin, 1925) are included in sodic amphiboles of the Vanoise cover (Briançonnais zone), so that part of the sodic amphiboles must be younger than Late Cretaceous.

3. Clastic fragments of glaucophane, glaucophane-lawsonite and lawsonite-pumpellyite-bearing meta-ophiolites are known in Oligocene and Miocene conglomerates: e.g. in the Upper Provence (Chauveau and Lemoine, 1960; de Graciansky *et al.*, 1971), near Grenoble (Bocquet, 1966), and in the Po basin (Gabert, 1962). One glaucophane metamorphic phase has thus to be earlier than Early Oligocene.

4. The zeolites and pumpellyite of the "Taveyannaz" and "Champsaur sandstones" indicate an Early Miocene (Aquitanian) to Pliocene (Pontian) age of a

late, low stage of metamorphism (Martini and Vuagnat, 1965, 1970; Martini, 1968; Sawatzki and Vuagnat, 1971).

5. Microscopical petrographic observations in the internal structural zones of the Western Alps show the sequence (see Fig. 1):

omphacite ± glaucophane	high pressure facies = Eoalpine metamorphism
↓	
blue amphibole + phengite ± lawsonite ± pumpellyite	|
↓	|
blue green amphibole	|
chlorite + albite	↓
biotite	greenschist facies

6. Rb—Sr and K—Ar radiometric data in the Bernhard zone and in the Mt Rosa massif (Hunziker, 1969, 1970, 1971; Hunziker and Bearth, 1969), in the Sesia zone and the Zermatt zone (Dal Piaz *et al.*, 1972; Hunziker, 1974), in the Mont Blanc massif (Krummenacher and Evernden, 1960; Baggio *et al.*, 1967; Leutwein *et al.*, 1970), in the Gran Paradiso massif (Krummenacher and Evernden, 1960), and in the Dora-Maira massif (Vialette and Vialon, 1964), point to an Eoalpine phase, and to two or more younger phases: (a) An Eoalpine phase of Cretaceous age (between 100 and 60 m.y.), is supported by radiometric measurements on sodic amphiboles and on white micas from the Zermatt ophiolites, the Sesia zone, also from the Dora-Maira massif. (b) Two or more younger phases are found, one around 38 m.y. (correlatable in time with the Lepontine thermal culmination of the Central Alps; Jäger *et al.*, 1967; Jäger, 1970; Hunziker, 1970). (c) The youngest phase so far detected (Frey *et al.*, 1973; Hunziker, 1974) is of Oligocene-Miocene age. A review of the geochronologic data is given in Frey *et al.* (1974).

The Upper Cretaceous fossils found in blue amphibole crystal grains of the Vanoise massif mean that the 80–100 m.y. age of the oldest glaucophanes in the Zermatt zone may not be typical of all sodic amphiboles of the Western Alps.

In conclusion it can be stated that at least two crystallization stages of sodic amphiboles have to be assumed in the Western Alps: an Eoalpine stage coeval with, and somewhat post-dating the eclogitic assemblages, and a later stage. It was interesting to study the distribution of these different ages, not only in blue amphiboles but also in other minerals of the same rocks and structural units. Geologic tectonic inferences concerning the thermobaric history of the Western Alpine belt have also been drawn.

Sampling

A list of samples with localization, parageneses, stratigraphic age, and structural origin of the host-rocks are given in Table 1. Samples were chosen in order to represent most structural units, stratigraphic levels and lithological types of blue amphibole-bearing rocks in the Western Alps.

Separation of the minerals was carried out by electromagnetic, electrostatic and density techniques. When possible, two different minerals of the rock were measured: amphibole-white mica, amphibole-chlorite, amphibole-pyroxene and white mica-biotite pairs.

The chemical analyses and/or physical characteristics of most of these minerals are found in Bocquet (1974, and in prep.). The results of these mineralogical investigations are summarized as follows.

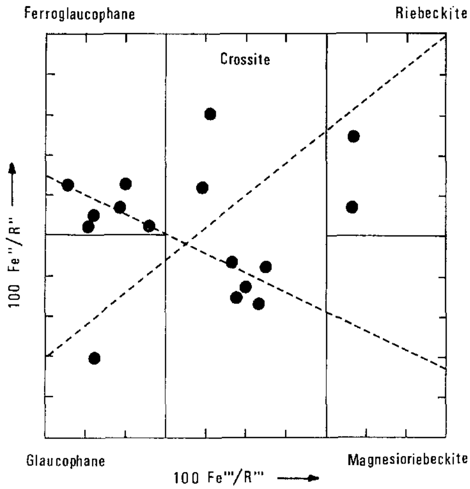

Fig. 2. Position of glaucophane s.l. chemical analyses in the Miyashiro's diagram. Tie-lines according to Bocquet (1974)

Blue amphiboles (Fig. 2) are described as glaucophane s.str., ferroglaucophane, crossite, magnesioriebeckite and riebeckite, approximately plotting along the tie-lines $Gl_{80}Fegl_{20}$—Rb_{100}, and $Fegl_{65}Gl_{35}$—$Mgrb_{82.5}Rb_{17.5}$. Their Fe'''/R''' and Fe''/R'' ratios are at least partly controlled by the host-rock composition. The actinolite content is going up to 24% in some samples from ophiolitic rocks. A strong zonation is frequent, the most common pattern, as revealed by microprobe studies, being a decrease of the Fe-content, with a concomitant increase of Al and Mg to the rim, but the reverse may also be found.

Bulk chemistry of white micas is mainly phengitic in Triassic and post-Triassic stratigraphic layers, i.e. rocks having suffered only Alpine metamorphism. The polymetamorphic rocks possess muscovitic to phengitic white micas, with possibly both pre-Alpine muscovite and Alpine phengite, as the b_0 spacings also seem to confirm (Sassi *et al.*, in Bocquet *et coll.*, 1974).

Chlorites have between 2.1 and 3.1 Al^{IV}, and between 2.0 and 5.2 (Fe_{tot} + Mn), according to chemical analyses, and/or basal spacings and b_0 parameter. They are oxidized chlorite, ripidolite and pycnochlorite according to Hey's (1954) classification, or sheridanite, clinochlore, ripidolite and brunsvigite according to Foster's (1962) classification.

Blue-green amphiboles are subcalcic, mainly actinolites to actinolitic hornblendes. The here measured sodic pyroxene is an aegyrine with 5% mol. jadeite and 6% mol. diopside-hedenbergite. No chemical analysis of the biotite is as yet available, but in a neighbour specimen (Gay, 1972) the $Mg/Mg + Fe_{tot}$ ratio is equal to 0.45.

Experimental Methods

1. Bern

Argon Measurements (see Hunziker, 1974): Argon was analyzed on a Varian Mat GD 150 mass-spectrometer and a glass line described by Purdy (1972), and calibrated according to

Tschedjemov *et al.* (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 6.31×10^{-6} cm^3 Ar^{40}rad/g STP.

Potassium Measurements (see Hunziker, 1974): For potassium contents above 2% the standard flame photometric technics described extensively by Purdy and Jäger (in prep.) was used. The attained accuracy was $\pm 1\%$ on duplicate analyses. For potassium contents below 2%, specially for alcali 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 blank of the overall procedure (chemistry and mass-spectrometry) is in the order of magnitude of 0.5 μg 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 1.19×10^{-4} mole K^{40}/mole K was used.

The 2σ error on the age determination was estimated to be $\pm 4\%$.

Rb—Sr Measurements (see Hunziker, 1974): For the Rb—Sr measurements the following physical constants were used:

$$Sr^{88}/Sr^{86} \text{ common} = 8.3752 \text{ (atoms)}$$
$$Sr^{86}/Sr^{84} \text{ common} = 17.49 \text{ (atoms)}$$
$$Sr^{87}/Sr^{86} \text{ common} = 0.7091 \text{ (atoms)}$$
$$Rb^{85}/Rb^{87} \text{ common} = 2.591 \text{ (atoms)}$$
$$\text{decay constant} = 1.47 \times 10^{-11}\, y^{-1}.$$

2. Geneva

a) *Potassium* was measured by flame photometry on an EEL instrument with monochromatic filters. Interferences due to Na were compensated by adding the same quantity of Na to the calibration solutions.

Each analysis has been completely repeated at least twice. Every twentieth sample a standard biotite has been analyzed to check the quality of the mother solutions used for the calibration curve.

b) The isotopic composition of *argon* has been measured with an AEI MS-10 mass-spectrometer. This instrument is on-line with a glass extraction and purification line. The sample has been melted by means of a high-frequency induction furnace in a Mo-crucible, and the gases purified on Cu—CuO and Ti traps. The mass-spectrometer is equipped with a 4100 gauss permanent magnet. As shown by Rex and Dodson (1970) the 4100 gauss magnet, instead of the 1650 gauss magnet normally used with this spectrometer, considerably improves the quality of the mass spectrum. The mass discrimination has been periodically corrected measuring atmospheric Ar prepared by purifying a small volume of air introduced into the line.

Every 10 to 15 measurements a standard biotite has been analyzed to control the depletion of the Ar^{38} spike, and the proper performance of the mass-spectrometer. The error of 4% given for the ages is calculated on double or triple measurements of K as well as Ar^{40}rad and Ar^{40}atm.

In Bern and Geneva the same constants for the age calculation were used.

3. Comparison of Geneva and Bern Results

n°		cm^3 Ar^{40}rad/g 10^{-6}	% Ar rad	% K	age m.y.
JB 1084 muscovite	Geneva	117.8	97.6	8.18	317 ± 13
	Bern	111.9	97.7		302 ± 12
P 207 muscovite	Geneva	28.50			
	Bern	27.86			

4. Grenoble

Potassium has been determined by flame spectrophotometry (Beckmann DU equipment).

Results

In Table 1 the K—Ar isotopic data are given, together with the calculated ages. The Rb—Sr data are listed in Table 2.

Discussion of the Results and Interpretation

Age results are plotted on a tectonic map of the Western Alps in Fig. 3. The results can be divided into six groups.

1. The oldest micas, being of Hercynian and of Caledonian apparent K—Ar age, come from the Ambin massif. The biotite with the Caledonian K—Ar apparent age proved to be of Permian age by Rb—Sr evidence. The higher K—Ar age is interpreted as a case of inherited argon.

2. Six white micas and one biotite of the Briançon-Bernhard zone seem to indicate a Permian event. A Permian phase of tectonics and metamorphism has already been postulated by Hunziker (1970) in the Mt Rosa nappe. One of these samples (n° 540), a "gneiss du Sapey", has two generations of white micas: a coarse Permian muscovite (265 m.y.), and a fine-grained Alpine phengite. The separation of the phengite was not too successful, leading to mixed Permian-Alpine ages for the fine-grained fractions (213 and 62 m.y.). The coexistence of Permian and Alpine white micas in the same rock shows that the Permian event may have been of a higher grade than the Alpine metamorphism. Otherwise all Permian mica ages would have been rejuvenated by the Alpine metamorphism. The "gneiss du Sapey", according to Ellenberger (1958) a Permian migmatization product of Permian material, was interpreted by Govi (in Bocquet *et al.*, in press) as granitoid intrusions of Permian age. These granitoids can be related to the general acid magmatic activity of Permian age throughout the Alps.

3. Ar-overpressure, or inherited Ar, was definitely found in blue amphiboles and other K-poor minerals from the pre-Alpine Vanoise basement, but also from the Versoyen zone, and, in one case, in a copper-mine in the Piemont Schistes lustrés. The Ar^{40}/Ar^{36} diagram (Fig. 4) of the analyzed minerals shows that inherited argon is present. All points show apparent ages above the 180 m.y. dotted isochrone line marking the maximum age of the pre-metamorphic emplacement of the Piemont ophiolites. Ar^{40}/Ar^{36} ratios of quartz, garnet, aegyrine, chlorite, and the negative slope of the "isochrones" of coexisting minerals can easily be explained with inherited Ar. The normal initial Ar^{40}/Ar^{36} ratio being around 295.5, this value should be found in K-free minerals. For a more detailed study of this problem, see Hunziker (1974). It is not yet clear if the 60–100 m.y. white K-mica ages of the Briançonnais basement are only due to argon-overpressure, as no K-free minerals from these rocks have been measured, and no cross-check with Rb—Sr has yet been done. Therefore these points are marked on the map as Ar-overpressure.

Ta. e 1. List of samples with localization, parageneses, and isotopic data (K-Ar). Samples * = K measured in Grenoble

JB n°	Lab n°	Locality	Rock-type and age
12	KA 555	Tignes, Villaret-du-Nial	quarz-micaschist, Trias
59	KAW 1100	St-Véran, Cu-mine	Na-amphibole and Na-pyroxene quartzite, Mesozoic
59-b	KAW 1182	,,	,,
88	KAW 1101	Roc du Bourget, near Modane	Na-amphibole limestone, Upper Jurassic
349	KA 554	Termignon, Gorges du Doron	Na-amphibole-garnet micaschist, pre-Westphalian
484	KA 551	Val d'Isère, pont St-Charles	phengite-chlorite marble, Upper Cretaceous-Paleocene
516	KAW 1102	Pralognan, Nants	Na-amphibole micaschist, pre-Westphalian
526	KAW 1183	Termignon, Bellecombe	Na-amphibole micaschist, pre-Westphalian
526	KAW 1103	,,	,,
540 (.063-I)	KA 547	Modane, fort du Replaton	K-feldspar-white mica-orthogneiss, Permian
540 (.063-II)	KA 546	,,	,,
540 (.250)	KA 545	,,	,,
565	KA 556	Tignes, le Saut	quarz-micaschist, Trias
630	KA 552	Charmaix, Pas du Roc	quarz-micaschist, Trias
662	KAW 1104	Ulzio, molino della Beaume	Na-amphibole marble, Trias
662	KAW 1184	,,	,,
667	KAW 1105	Acceglio, colle di Val Fissela	Na-amphibole calcschist, Upper Jurassic
673	KAW 1185	St-Véran, Roche Blanche	Na-amphibole-lawsonite meta-ophiolite, Mesozoic
685	KAW 1106	Termignon, lac des Gorges	Na-amphibole vein, pre-Westphalian
685	KAW —	,,	,,
698	KA 554	Aussois, col d'Aussois	quartz-micaschist, Upper Permian
706	KAW 1107	Aussois, carrière des Lozes	Na-amphibole marble, Upper Cretaceous-Paleocene
706	KAW 1186	,,	,,
718	KAW 1108	Bramans, cols de Bellecombe-Arella	Na-amphibole-magnetite marble, Upper Jurassic

numbered KAW were measured in Bern, samples numbered KA were measured in Geneva.

Mineral	Ar^{40}rad/g $cm^3 \cdot 10^{-6}$ STP	% Ar rad	% K	Ar^{40}/Ar^{36}	$K^{40}/Ar^{36} \cdot 10$	age (m.y.)
phengite	15.27	79.2	8.63	1563.0	555.3	44 ± 2
riebeckite	0.464	4.2	0.072	368.0	6.35	154 ± 47
aegyrine	0.432	35.1	0.0055	481.5	1.59	> 2000
crossite	0	0	0.080	290.7	14.5	—
ferrimuscovite	81.28	96.5	7.72*			247 ± 10
phengite	15.59	87.7	7.86*	2212.4	745.5	49 ± 2
ferroglaucophane	4.96	70.9	0.115	1051	12.9	~900
crossite	0.79	54.7	0.083	723.0	31.1	226 ± 16
ferrimuscovite + paragonite	45.19	96.9	5.54			194 ± 8
white mica	73.47	97.0	8.87			213 ± 8
phengite	22.08	91.6	8.67	3507	350	62 ± 2
white mica	96.44	95.0	8.49			265 ± 11
phengite	14.70	90.6	9.08*	1898.8	764.1	40 ± 2
phengite	15.32	88.3	8.69*	3438.9	1293.0	45 ± 2
crossite	0.151	14.5	0.046	359.5	8.07	68 ± 19
chlorite	0.044	3.0	0.209	310.2	22.21	5 ± 7
riebeckite	0.488	8.5	0.29	328.6	11.3	38 ± 18
blue amphibole	0.097	12.7	0.035	367.9	10.0	69 ± 22
crossite	5.92	81.0	0.069	1630	11.60	~1800
quartz	6.47	91.6	n.d.	3816	0	
muscovite	13.09	87.4	8.18*	2344.1	899.4	40 ± 2
crossite	0	0	0.035	311.5	4.95	—
chlorite	0.0135	2.7	0.058	314.0	10.85	6 ± 9
crossite	0.025	10.4	0.033	348.7	6.89	19 ± 7

Table 1 (continued)

JB n°	Lab n°	Locality	Rock-type and age
728	KAW 1109	Charmaix, Petit Argentier	Na-amphibole quartz-schist, Mesozoic
767	KA 550	Termignon, glacier de l'Arpont	muscovite vein
840	KAW 1187	Molines-en-Queyras, Longet	Na-amphibole marble, Mesozoic
843	KAW 1110	Molines-en-Queyras, Longet	glaucophane-lawsonite meta-ophiolite, Mesozoic
854	KAW 1111	Ceillac, ravin des Prés Bergers	Na-amphibole schist, Mesozoic
860	KAW 1112	Ceillac, col des Prés Bergers	Na-amphibole meta-ophio-lite, Mesozoic
881	KAW 1113	Mt Cenis, fort de la Turra	Na-amphibole-dolomite vein
923	KAW 1188	Termignon, glacier de l'Arpont	garnet glaucophanite pre-Westphalian
949	KAW 1114	Termignon, Arpont N	Na-amphibole micaschist, pre-Westphalian
955	KAW 1189	Bessans, Avérole, Entre-Deux-Ris	amphibolite, meta-ophiolite, Mesozoic
955	KAW 1190	,,	,,
956	KAW 1115	Val d'Isère, sources de l'Isère	amphibole-epidote meta-ophiolite, Mesozoic
965	KAW 1191	Pralognan, cirque du Dard	Na-amphibole micaschist, pre-Westphalian
965	KAW 1116	,,	,,
981	KAW 1192	Villarodin	Na-amphibole meta-gabbro, Mesozoic
1012	KAW 1193	Meyriès, vallon de Péas	Na-amphibole-lawsonite calcschist, Mesozoic
1012	KAW 1194	,,	,,
1028	KAW 1195	Tignes, vallon du Pâquier	Na-amphibole-magnetite limestone, Upper Cretaceous-Paleocene
1034	KAW 1196	Ste-Foy, glacier de l'Avernet	Na-amphibole micaschist, pre-Westphalian
1034	KAW 1197	,,	,,
1045	KAW 1198	Bourg-St-Maurice, pte Clapey	Na-amphibole-jadeite-chloritoid schist, Mesozoic
1045	KAW 1199	,,	,,
1084	KA 548	Bramans, saut de l'Oulle	garnet-biotite micaschist pre-Westphalian

Mineral	Ar^{40}rad/g $cm^3 \cdot 10^{-6}$ STP	% Ar rad	% K	Ar^{40}/Ar^{36}	$K^{40}/Ar^{36} \cdot 10^3$	age (m.y.)
ferroglaucophane	0.157	17.4	0.058	372.4	13.1	67 ± 15
ferrimuscovite	95.97	98.4	9.13*			247 ± 10
ferroglaucophane	0.088	9.0	0.021	337.5	4.49	104 ± 46
glaucophane	0	0	0.028	295.0	8.53	—
crossite	0.137	17.3	0.086	375.7	19.8	39 ± 9
blue amphibole	0.0073	4.1	0.023	317.4	2.23	8 ± 8
blue amphibole	0.0044	2.8	0.115	323.2	18.02	1 ± 2
	0	0	0.115	323.7	23.7	—
blue amphibole	3.08	68.9	0.733	985.5	122.6	102 ± 6
ferroglaucophane	2.52	50.7	0.150	616.5	13.75	420
ferro-actinolite	0.26	12.4	0.039	363.6	8.41	80 ± 26
chlorite	0.044	1.3	0.182	299.0	8.50	6 ± 19
ferro-hornblende	0.147	17.5	0.162	378.2	33.36	23 ± 5
ferroglaucophane	1.47	70.2	0.088	1163	36.66	380
phengite	30.56	92.3	8.12			92 ± 4
blue amphibole	0.055	10.2	0.073	359.2	26.31	19 ± 7
blue amphibole	0.064	13.8	0.138	403.2	62.26	11 ± 3
white mica	16.02	87.3	8.41	2377	827.3	47 ± 2
blue amphibole	0.0075	4.1	0.031	333.5	10.81	6 ± 6
blue amphibole	2.68	73.1	0.091	1180	22.17	620 ± 34
white mica	17.60	71.6	8.28	1047	267.7	53 ± 3
ferroglaucophane	0.305	24.3	0.038	428.4	8.91	193 ± 32
chlorite	0.138	5.5	0.043	315.6	3.61	79 ± 6
biotite	113.14	96.8	5.62			449 ± 18

Table 1 (continued)

JB n°	Lab n°	Locality	Rock-type and age
1084	KA 549	,,	,,
1084	KAW	,,	,,
	KA 52	St-Luc	"Casanna" schist
	KA 65	St-Luc	"Casanna" schist
	KA 66	Thyon, 113°100/594°410	"Thyon" gneiss
	KA 198	Bagnes valley, 83°500/594°500	"Casanna" schist
	KA 199	Bagnes valley	"Casanna" schist
	KA 200	Bagnes valley, Mauvoisin, 87°850/595°200	"Casanna" schist
	KA 202	Bagnes valley, 95°750/592°050	"Casanna" schist
	KA 205	Bagnes valley, coupole de Boussine, 91°450/593°100	"Casanna" schist
	KA 206	Bagnes valley, 95°600/591°950	"Casanna" schist
	KA 207	Bagnes valley, Mauvoisin, 94°795/592°550	quartzite
	KA 418	Arolla glacier, 91°750/599°100	"Arolla" gneiss

Table 2. Rb—Sr data and age results of 3 micas of the Western Alps

JB n°	Lab n°	Locality	Rock-type and age
12	KAW 1323	Tignes, Villaret-du-Nial	quartz-micaschist, Trias
565	KAW 1321	Tignes, le Saut	quartz-micaschist, Trias
1084	KAW 1322	Bramans, saut de l'Oulle	garnet-biotite micaschist, pre-Westphalian

4. Normally blue amphiboles of the Mesozoic cover show no sign of inherited Ar, as can be seen in Fig. 5. The initial ratio Ar^{40}/Ar^{36} in these rocks being around 295, the apparent K—Ar ages in this case are true ages. The black field marking the initial Ar^{40}/Ar^{36} ratio represents 20 analyses. We find an upper field of 78 to 100 m.y. for the oldest analyzed glaucophanes s.l. and blue-green amphiboles from the Piemont zone (Schistes lustrés and ophiolites). The dotted fields, separated by marked gaps from the 78 to 100 m.y. field, represent the age groups of the remaining analyzed amphiboles (see Figs. 6 and 8). As the oldest parageneses comprise jadeite + quartz + lawsonite + glaucophane, the Late Cretaceous event must be a high pressure metamorphism.

5. A second field (Fig. 6), between 39 and 50 m.y., coincides with the mica field (Fig. 7) of 40–53 m.y. (K—Ar). These age values are slightly higher than the Lepontine phase of 38 ± 2 m.y. (Rb—Sr) in the Central Alps (Hunziker, 1970;

Mineral	Ar^{40}rad/g $cm^3 \cdot 10^{-6}$ STP	%Ar rad	%K	Ar^{40}/Ar^{36}	$K^{40}/Ar^{36} \cdot 10^3$	age (m.y.)
white mica	117.77	97.6	8.18			317 ± 13
,,	111.9	97.7	,,			301 ± 12
mica	24.076	92.3	2.67			213 ± 8
green mica	23.577	48.3	2.72			205 ± 8
biotite	8.849	74.6	4.72	1287.4	402.6	47 ± 2
white mica	7.872	62.2	4.60	799.5	252.8	42 ± 2
white mica	9.463	51.0	5.05	595.6	112.5	46 ± 2
dark minerals	3.974	54.5	2.48	657.9	158.3	40 ± 2
white mica	18.059	53.7	4.69			94 ± 4
white mica	11.899	45.9	4.34			68 ± 3
dark minerals	2.707	12.0	0.58			113 ± 5
white mica	10.822	73.2	7.92	954	241.6	33 ± 1
light minerals	6.086	66.1	4.53	884.1	305.6	33 ± 1

Mineral	Rb^{87} (ppm)	Sr^{87} rad (ppm)	% rad	Sr common (ppm)	age (m.y.)
phengite	107.1	0.0567	11.8	6.09	36.0 ± 5.7
phengite	103.1	0.0540	15.2	4.34	35.6 ± 4.3
biotite	115.9	0.4593	29.4	15.9	269 ± 16

Jäger, 1970). Either the Eocene-Oligocene metamorphic phase was earlier in the Western Alps than in the Central Alps, or we are dealing here with a minor case of inherited argon. Rb—Sr and K—Ar measurements of two micas of this age group have shown that the Rb—Sr age in both cases is lower than the K—Ar ages. The apparent K—Ar ages of the two phengites are 44 ± 2 and 40 ± 2 m.y. The Rb—Sr ages of the same micas are 36.0 ± 5.7 and 35.6 ± 4.3 m.y. This implies that both the Eocene-Oligocene phase in the Western and in the Central Alps are contemporaneous, and that the K—Ar data show slight traces of inherited argon.

6. The third field (Fig. 8) covers ages between 15 and 30 m.y., yielding strong evidence for a Miocene event in the Western Alps. A Miocene event of tectonics and recrystallization has been found in the Helvetic domain by Frey *et al.* (1973). Minerals yielding this Oligocene to Miocene ages are crossite and blue-green

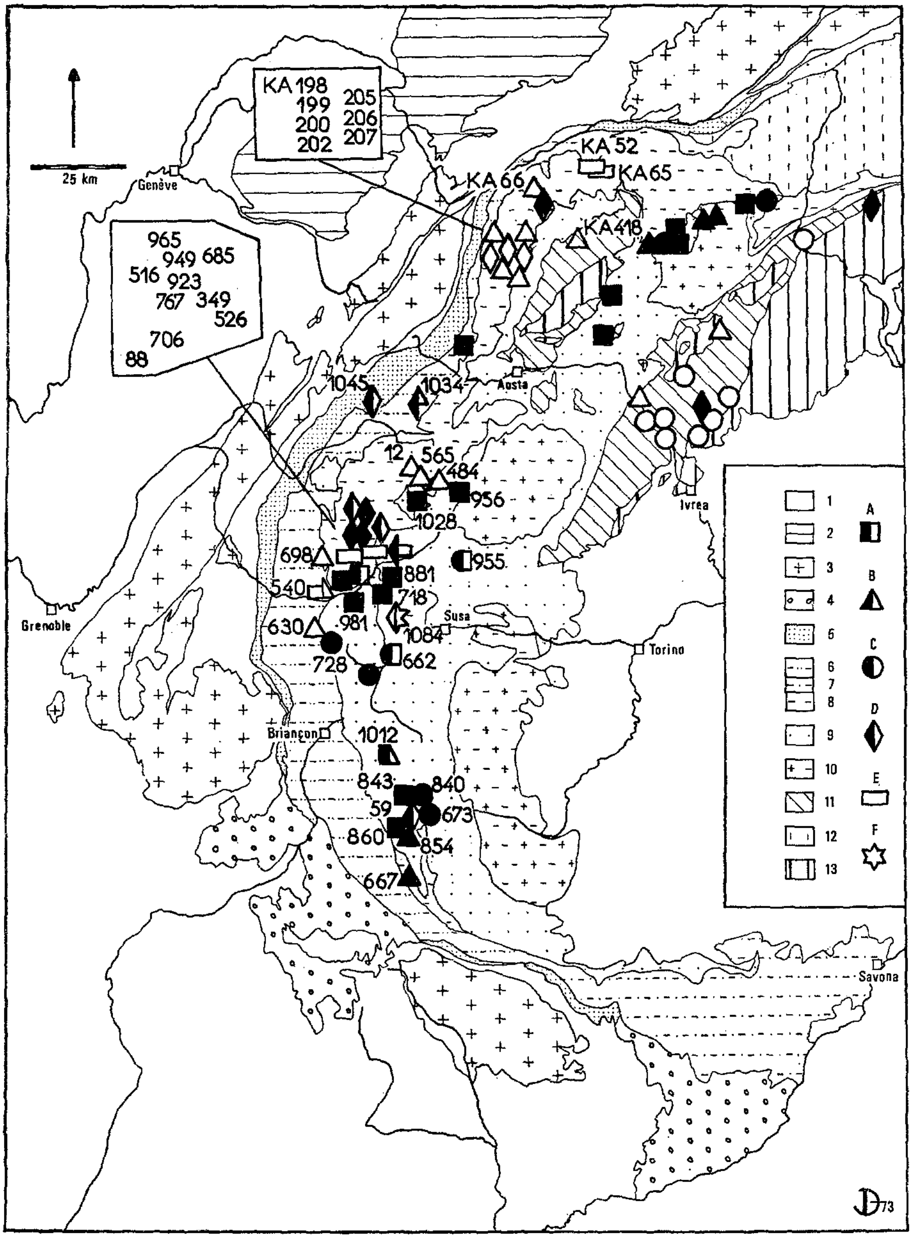

Fig. 3. Age results: new data from this paper and data already given in the literature for amphiboles and micas (Hunziker, 1974). KA numbers = Geneva, and numbers = JB refer to new data. For points without numbers see Hunziker (1974). Black symbols refer to amphibole ages; open symbols refer to mica ages. The quartz, aegyrine and chlorite analyses are presented as open symbols. Age symbols: *A* 15–30 m.y.; *B* 39–53 m.y.; *C* 78–100 m.y.; *D* argon overpressure; *E* Permian ages; *F* Hercynian ages

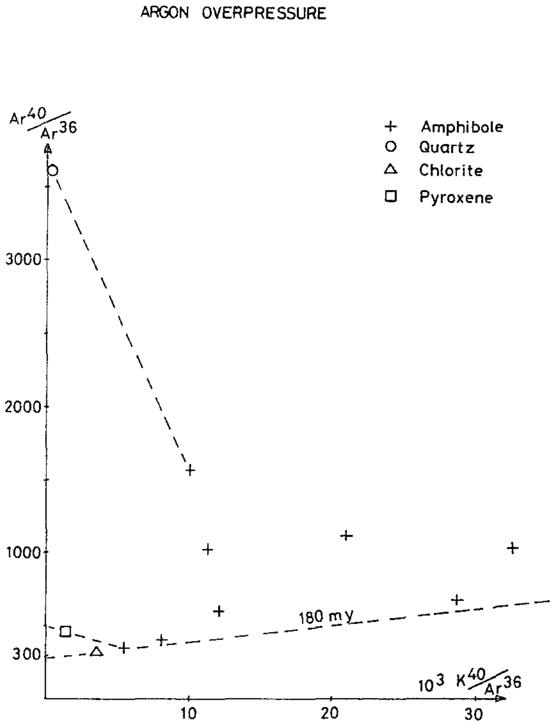

Fig. 4. Ar^{40}/Ar^{36} versus K^{40}/Ar^{36} isochron plot of minerals from the basement units of the Western Alps, showing great amounts of inherited argon

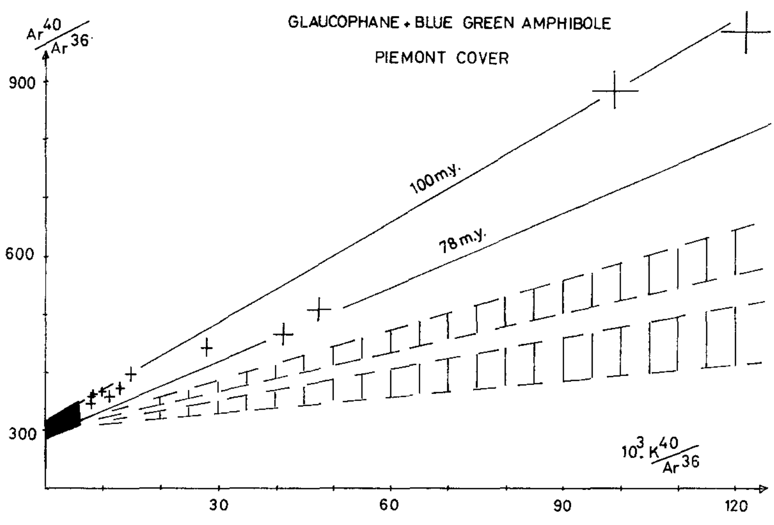

Fig. 5. Ar^{40}/Ar^{36} versus K^{40}/Ar^{36} isochron plot of glaucophane s.l. and blue-green amphibole of the Piemont cover, yielding Eoalpine ages of 78 to 100 m.y. The normal initial values of K-poor to K-free minerals show that an interpretation as true ages is justified. The stippled areas represent the younger amphibole ages groups (see Figs. 6 and 8). The black field marking the initial Ar^{40}/Ar^{36} ratio represents 20 analyzes

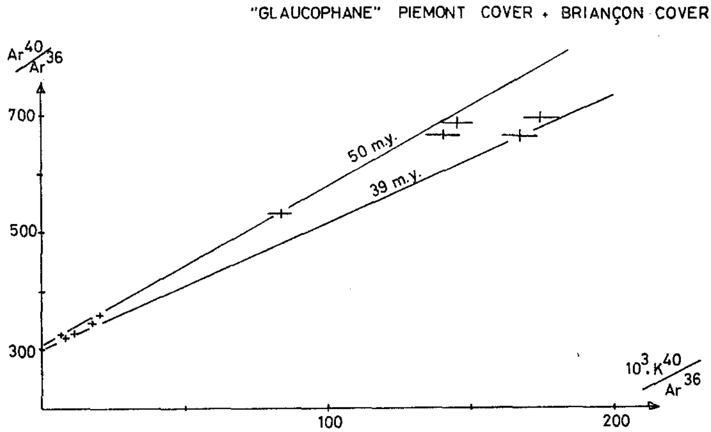

Fig. 6. Ar^{40}/Ar^{36} versus K^{40}/Ar^{36} isochron plot of glaucophane s.l. of the Piemont and Briançon cover, yielding ages of 39–50 m.y.

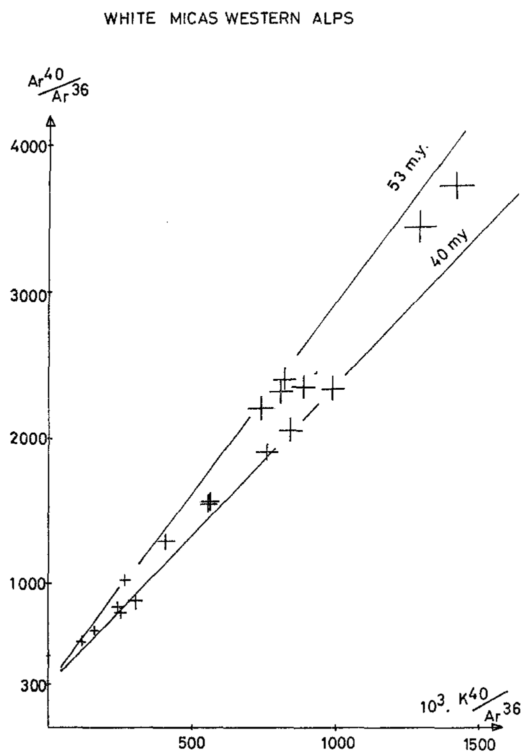

Fig. 7. Ar^{40}/Ar^{36} versus K^{40}/Ar^{36} isochron plot of 40–53 m.y. old white micas of the Western Alps. The lower Rb—Sr age of these white micas (see Table 2) shows that at least a minor amount of inherited argon may be present in both glaucophanes s.l. and white micas, and that the age of the Eocene/Oligocene phase of metamorphism in the Western Alps coincides with the Lepontine phase of the Central Alps

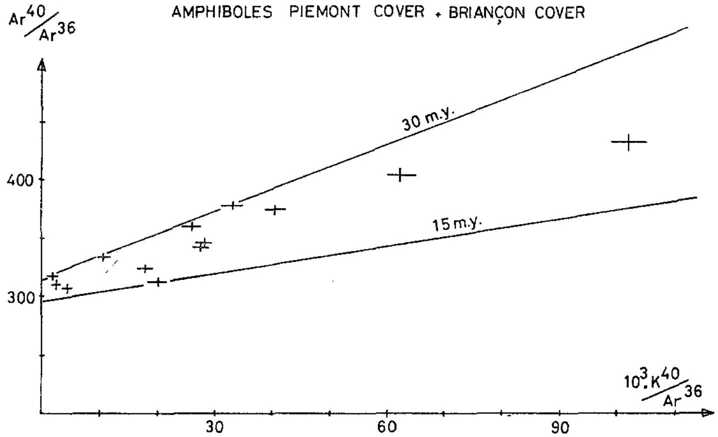

Fig. 8. Ar^{40}/Ar^{36} versus K^{40}/Ar^{36} isochron plot of amphiboles of the Western Alps yielding ages of 15 to 30 m.y., thus giving evidence for an Oligocene to Miocene event in the Western Alps

amphibole. As already mentioned in the introduction, at least two crystallization stages of blue amphiboles must be taken into consideration. A first generation would explain the Late Cretaceous age group of 78–100 m.y., in good agreement with the mica ages between 60–90 m.y. found by Hunziker (1974) in the Sesia zone. A second generation of glaucophane could either have grown during the Eocene-Oligocene, or during the Miocene event. It seems more likely that the second generation has grown during the Eocene-Oligocene metamorphism, and has just suffered Ar-loss during the Miocene event. In the Mt Rosa region Chadwick (1974) found that the orientation of the youngest blue amphiboles is connected with the Mischabel-backfold. The marked effect of the "rétrocharriage" in the Western Alps could well account for the youngest data obtained. Unfortunately, structural data from this region are still too scarce.

The field of distribution of blue amphiboles in the Western Alps (see Fig. 1) can be subdivided into two areas: an external part towards the Dauphiné-Helvetic domain, containing no eclogites, and an internal part with wide distribution of eclogites. This fact seems to mark a temperature drop during the high pressure phase towards the external parts. In the external part no omphacite has been found, so that temperature must have been around 200–400° C, at pressures above 8 kb, for the association jadeite + quartz. As the jadeite-bearing Piemont nappe (ophiolites and Schistes lustrés) represents the highest structural unit in this part of the Alps, a lithostatic overburden cannot account for this Late Cretaceous high pressure—low temperature metamorphism. Therefore a subduction model, as proposed by various authors (Dewey and Bird, 1970; Laubscher, 1971; Ernst, 1971, 1973; Martini, 1972; Dal Piaz *et al.*, 1972; Oxburgh, 1972) seems to be a plausible explanation.

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