The age of the Mont-Blanc granite (Western Alps) : a heterogeneous isotopic system dated by Rb-Sr whole rock determinations on its microgranular enclaves

SCHWEIZ. MINERAL. PETROGR. MITT. 69, 3–13, 1989

The age of the Mont-Blanc granite (Western Alps): a heterogeneous isotopic system dated by Rb-Sr whole rock determinations on its microgranular enclaves

by *François Bussy*[1], *Urs Schaltegger*[2] and *Christian Marro*[3]

Abstract

New Rb-Sr whole rock age data have been obtained for the Mont-Blanc calc-alkaline Hercynian granite. Different facies of the granite have been sampled, as well as locally abundant microgranular enclaves of magmatic origin. The analytical data for the granite and for some of the enclaves are scattered within the Sr evolution diagram, which points to isotopic disequilibrium. Other enclaves form a homogeneous system which gives an age of 316.1 ± 19.5 Ma and an initial $^{87}Sr/^{86}Sr$ ratio of 0.7058 ± 0.0005. The following evolution is plausible:

– individualization of microgranular enclaves due to the dismembering of mafic synplutonic dikes within the granitic magma;

– complete isotopic equilibrium between granite and enclaves during a late-magmatic stage;

– remobilization of the granite and certain enclaves in a post-magmatic stage (?) and during Alpine orogenesis. Certain enclaves are not affected and retain the original characteristics of the system.

The 316 Ma age of these "relics" and their initial ratio of 0.7058 are therefore thought to be valid for the granite as well. These results are similar to those obtained for other calc-alkaline Hercynian plutons in Western Europe. They indicate an origin for the granitic magma in the deep crust with involvement of mantle-derived material in unknown proportions, represented by the microgranular enclaves.

Keywords: Calc-alkaline granite, enclaves, Rb-Sr age, Mont-Blanc, Western Alps.

1. Introduction

The Mont-Blanc crystalline massif is situated in the external zone of the Western Alpine arc (Fig. 1). It includes a complex polymetamorphic basement (VON RAUMER, 1984) into which the calc-alkaline potassic Mont-Blanc granite intruded at the end of the Hercynian orogeny. This granite is generally coarse-grained, with alkali feldspar megacrysts. It was deformed and locally mylonitized, probably at time of emplacement or just after (BELLIERE, 1987). During the alpine orogeny, which is responsible for the general uplift of the massif, further deformation occurred with the development of greenschist facies metamorphism (VON RAUMER, 1969, 1974). Fluid inclusions in fissure quartz crystals suggest temperatures of the order of 400°C and pressures around 2,5 Kb (POTY et al., 1974).

As do most calc-alkaline granites in the world, the Mont-Blanc granite contains many dark microgranular enclaves (using DIDIER's terminology, 1973) or microgranitoid enclaves (VERNON, 1983), whose origin is the subject of debate. They have been considered to be restites, xenoliths from an underlying mafic body, hornfelsic fragments of country rock, segregations within the granitic magma or blobs of an independent basic magma in liquid coexistence with the granitic magma. VERNON (1983) refers to these different interpretations. JACQUEMIN and BELLIERE (1984) have concluded that the microgranular enclaves of the Mont-Blanc are magmatic in origin, and so have all those who have recently studied enclaves of the calc-alkaline Hercynian massifs of Western Europe. This interpretation receives confirmation in the fact that certain enclaves and some late micromonzodioritic dikes within the granite are geochemically identi-

[1] Institut de Minéralogie, Université de Lausanne-BFSH2, CH-1015 Lausanne.
[2] Abteilung für Isotopengeologie, Universität Bern, Erlachstrasse 9a, CH-3012 Bern.
[3] ABA-GEOL SA, CH-1530 Payerne.

cal (BUSSY, 1987). The same study has also revealed the existence in the Mont-Blanc granite of two petrographically and chemically distinct families of microgranular enclaves.

BAGGIO et al. (1967) published Rb-Sr isotopic data on the Mont-Blanc granite. The scatter of their results requires, however, that the age of 313 Ma, obtained for the granite, be considered with caution. The present study was undertaken on the granitoids, with the aim to obtain a more satisfactory isochron than that of BAGGIO et al. (1967) and also on the two families of enclaves, in order to determine:

1. the compatibility of the isotopic data with a magmatic origin of the enclaves,
2. possible internal coherence within the two groups of enclaves and their conceivable isotopic distinction, and
3. the likelihood of isotopic equilibrium between granite and enclaves.

2. General description of the rocks

2.1. GRANITOIDS

According to MARRO (1987), the Mont-Blanc intrusion includes:

- a major *central* facies (about 80% of the visible volume), leucocratic, porphyritic, with alkali feldspar megacrysts several cm long, often aligned, with a matrix composed of grains 0.5 to 1 cm in diameter;
- an equigranular *border* facies, similar in texture to that of the matrix of the central facies, which is sometimes lacking where the central facies is in tectonic contact with the basement;
- dikes, several meters in width, of a hololeucocratic microgranite common in the eastern part of the massif, locally porphyritic, with corroded quartz phenocrysts;
- enclaves and monzodioritic dikes described below in section 2.2.

Mineralogically, the border facies differs from the central one only in its lack of phenocrysts. Both have undergone locally strong Alpine deformation and recrystallization. The plagioclase is fractured, saussuritic, albitic (originally An_{30-35}); the large alkali feldspars (microcline with triclinicity > 0.90) show fractures filled with quartz, albite and green biotite. Quartz forms large subhedral, corroded crystals or is interstitial, but always deformed. Biotite is green, often recrystallized, with inclusions of secondary sphene. It sometimes forms aggregates pseudomorphic after amphibole. Neoformation of stilpnomelane has also been observed. Accessories are: apatite, sphene, zircon,

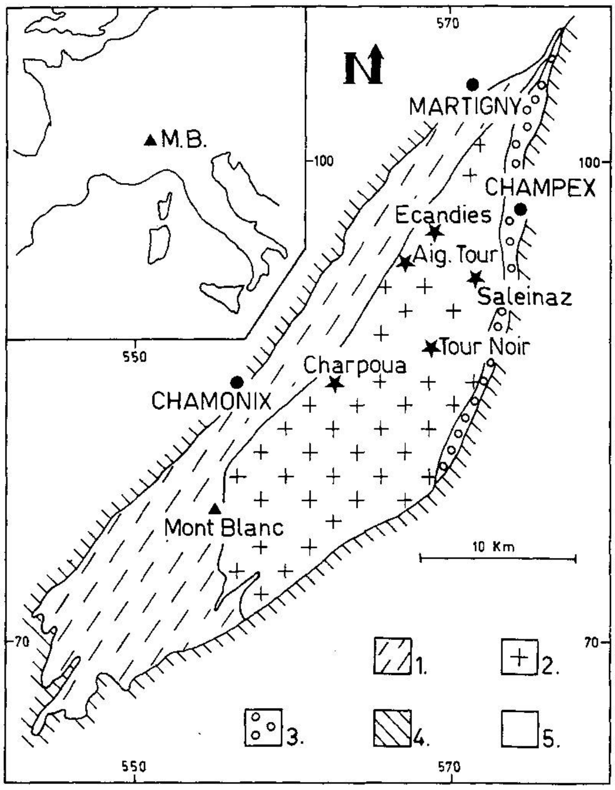

Fig. 1 Simplified geological map of the Mont-Blanc area with sample localities (black stars). 1 = metamorphic basement, 2 = Mont-Blanc granite, 3 = rhyolite, 4 = Mesozoic rocks, 5 = Quaternary terrains.

allanite. Veinlets and fractures filled with chlorite, sericite and clinozoisite indicate circulation of fluids.

The internal zones of the intrusion grade into the external ones by slow decline of the size of the megacrysts and of the amount of plagioclase and biotite and by simultaneous increase in the quantities of quartz and alkali feldspar. These tendencies are confirmed by geochemistry (MARRO, 1987). CaO, FeO, Ba, Sr and Zr in particular decrease from center to edge of the intrusion, in contrast to SiO_2, K_2O and Rb. The marginal rocks however, do not always plot on the trends for K_2O, Ba, Rb, Sr and Zr for example as defined by the central and intermediate varieties. These discrepancies possibly reflect complex interaction with country rock (assimilation, circulation of fluids). MARRO (1987) considers the general organization of the massif to be due to flow differentiation during intrusion and the border facies to represent a rapidly cooled zone.

2.2. THE DARK MICROGRANULAR ENCLAVES

The microgranular enclaves of the Mont-Blanc (JACQUEMIN & BELLIERE, 1984) have all the usual characteristics of microgranular enclaves of calc-

Tab. 1 XRF analyses of the enclave samples. In brackets, limits of detection (ppm) for trace elements. If FeO not reported, total iron as Fe_2O_3.

	Magnesian enclaves							Ferroan enclaves				
KAW	2895	2896	2897	2899	2900	3114	3119	2898	3115	3116	3117	3118
(wt-%)												
SiO2	55.22	67.31	55.75	56.67	56.20	65.47	58.95	62.52	55.87	59.66	55.85	62.65
TiO2	1.02	0.55	1.06	1.03	1.05	0.71	0.93	0.82	1.23	0.98	1.22	0.82
Al2O3	16.19	14.93	16.43	16.33	16.64	15.29	16.13	15.84	16.85	16.30	17.04	15.77
Fe2O3	2.97	1.58	7.64	7.39	7.60	4.39	6.63	2.88	9.38	7.52	9.25	6.19
FeO	4.08	2.25						3.50				
MnO	0.12	0.06	0.13	0.13	0.12	0.09	0.12	0.17	0.20	0.18	0.22	0.13
MgO	5.19	1.28	4.65	4.36	4.66	1.63	3.40	1.87	2.49	2.04	2.48	1.73
CaO	6.69	2.65	6.71	6.37	6.67	3.22	5.79	2.97	4.17	4.31	4.42	3.71
Na2O	3.78	3.38	3.24	3.83	3.44	3.49	3.14	4.69	4.41	3.88	4.52	4.30
K2O	2.55	4.40	2.72	2.38	2.35	3.98	3.38	2.97	3.39	3.10	3.20	2.69
P2O5	0.22	0.17	0.21	0.22	0.21	0.24	0.24	0.36	0.50	0.39	0.50	0.32
L.o.i.	1.83	1.11	1.26	1.19	1.00	1.19	0.90	1.32	1.05	1.09	1.02	1.07
TOTAL	99.86	99.67	99.80	99.90	99.94	99.70	99.61	99.91	99.54	99.45	99.72	99.38
(ppm)												
Nb [4]	11	15	13	13	14	19	11	19	30	31	30	20
Zr [4]	183	214	190	190	191	228	222	334	333	294	331	299
Y [5]	34	42	37	36	36	52	37	47	86	84	88	49
Sr [4]	298	187	310	299	320	229	344	174	136	197	143	162
Rb [4]	208	212	130	174	116	212	150	381	496	430	469	325
Th [2]	5	7	6	8	6	16	10	13	11	18	12	15
Zn [4]	77	53	71	71	70	48	74	103	127	103	123	80
Ni [7]	17	9	21	20	20	16	11	17	23	18	18	12
Cr [14]	92	16	104	95	99	22	59				37	
V [3]	157	72	158	153	164	80	140	89	138	108	133	92
Ce [15]	92	76	101	93	86	100	100	47	66	77	110	90
Nd [7]	23	11	42	35	37	38	36	32	81	52	72	58
Ba [13]	456	710	546	527	527	649	722	238	290	259	262	333
La [2]	55	53	57	56	58	50	31	32	44	24	50	45
Sc [1]	26	12	27	26	29	13	25	11	18	13	18	12

alkaline granites (DIDIER, 1973: VERNON, 1983). Mineralogical, textural and geochemical criteria allow the individualization of two populations (BUSSY, 1987): a) *hornblende and biotite* or *magnesian enclaves,* with a relatively high MgO/totFeO ratio of 0.6–0.7 and b) *biotite* (exclusively) or *ferroan enclaves,* with a lower MgO/totFeO ratio of 0.3 (Fig. 3).

a) The hornblende and biotite enclaves of the magnesian trend:

The size of these enclaves is generally in the meter to decameter range. Their shape is often lobate, and they form swarms hundreds of meters in extent. Their modal composition is: labradorite (50%), pale green hornblende (25%), brown biotite (5–10%), quartz (10%), alkali feldspar (5–10%), hollow acicular apatite. They may contain large rounded crystals of quartz with reaction rims (ocelli), plagioclase, alkali feldspar and biotite identical to their counterparts in the host granite (from which they are derived according to JACQUEMIN & BELLIERE, 1984).

Geochemically, these enclaves are of the calc-alkaline type (Table 1) with compositions ranging from quartz diorite to granite (Fig. 2). They define a clear trend in the MgO/totFeO diagram (Fig. 3) as in other diagrams involving Mg, Al, Na, Zr, Sr, Rb and Cr. Important chemical gradients sometimes develop at the contact between enclaves and host granite (BUSSY, 1987).

The enclaves are the product of the dismembering of basic to intermediate synplutonic dikes intrusive into partially crystallized granitic magma. The thermal contrast related to this situation promotes rapid crystallization of the blobs of basic magma. Mingling (mechanical) and mixing (chemical) of acid and basic magmas occur before, during and after the formation of the enclaves. This view is based on the following arguments:

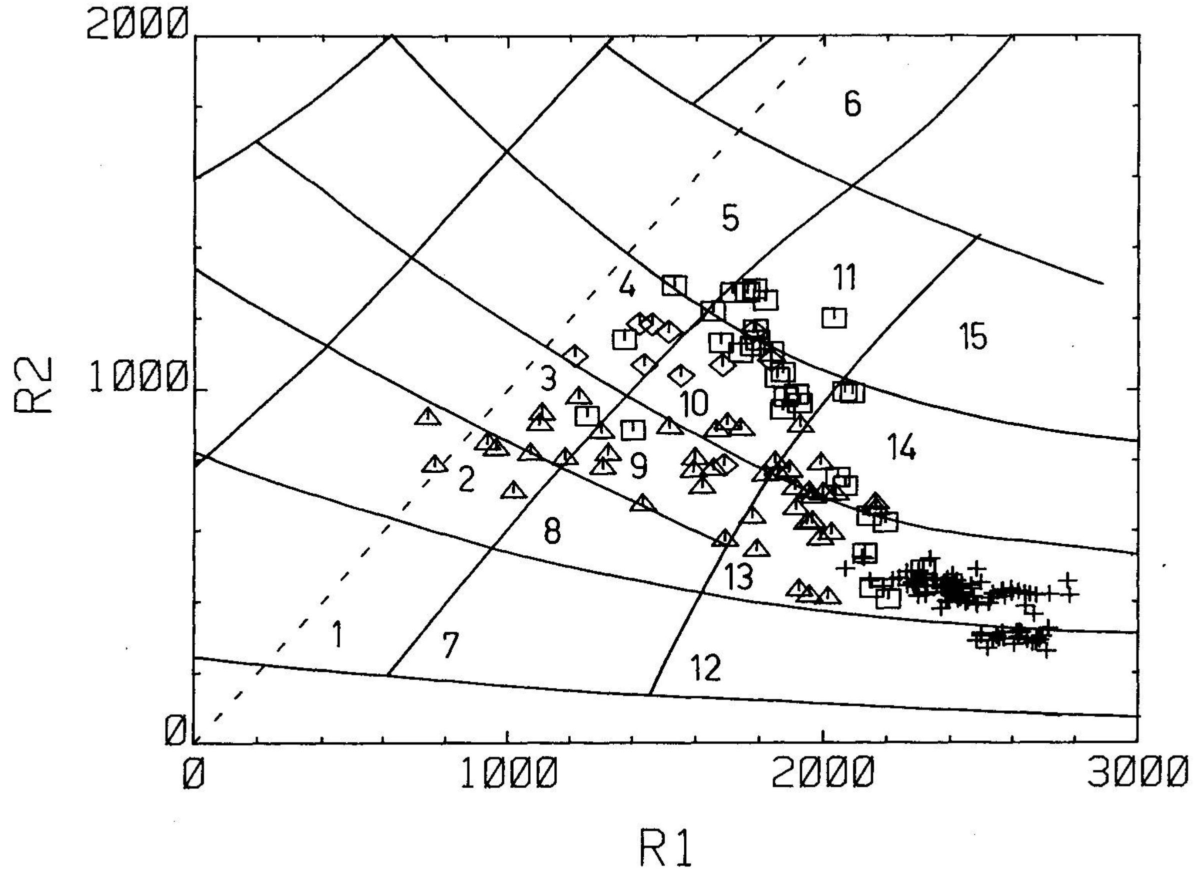

Fig. 2 Geochemical classification diagram of LA ROCHE et al. (1980), modified by STRECKEISEN (1981) with unpublished data and data from MARRO (1987). Squares: magnesian enclaves; triangles: ferroan enclaves; diamonds: basic dikes; crosses: undifferentiated granites. 1(7): alkaline syenite (qz-), 2(8): syenite (qz-), 3(9):monzonite(qz-), 4(10): monzodiorite (qz-), 5(11): diorite (qz-). 6: gabbro, 12: alkaline granite, 13: A and B granites, 14: granodiorite, 15: tonalite, qz = quartz, R1 = 4Si-11(Na+K)-2(Fe+Ti), R2 = 6Ca+2Mg+Al (in millications).

1) mineralogical and textural: acicular apatite (WYLLIE et al., 1962), doleritic texture, lobate shapes, crystals derived from the granite (= xenocrysts), dike swarms, implying rapid crystallization of a hybrid magma intruded as dismembered dykes into a colder mass of contrasting viscosity.

2) geochemical (BUSSY, 1987): the trends observed in the diagrams may be interpreted in terms of mixing; the granite contains late dikes identical in composition to that of the most basic enclaves which proves the existence of an independent magma; the chemical gradients at enclaves-granite contacts underscore the importance of chemical exchange.

3) structural: the enclaves are spherical if the granite is isotropic, ellipsoidal and oriented if the latter exhibits a magmatic flow structure, which suggests liquid state coexistence. The swarms lie approximately N20E, as do the late dikes, again stressing a relationship.

b) The biotite enclaves of the ferroan trend:

They differ from the magnesian enclaves in the following: smaller size (generally less than one meter), in smaller and more dispersed swarms, finer grain-size, generally indistinct igneous texture blurred by subsequent crystallization of epidote and greenish biotite (with some sericite) in plagioclase. The main mineralogical difference is the higher biotite content (15–25% in volume). They also contain: 50–60% albite+epidote, 10–15% interstitial quartz, a few percent of alkali feldspar, hollow acicular apatite, as well as the large granite-derived crystals also found in the hornblende-bearing enclaves.

Geochemically, the ferroan enclaves are quite different from the magnesian enclaves, both in classification (Fig. 2) and in geochemical diagrams, in particular for the MgO/totFeO ratio (Fig. 3). They probably also represent the crystallization of a variably hybridized magma, as suggested by the presence of xenocrysts and some clearly igneous textures. The geochemical trends, however, cannot be interpreted in simple mixing or crystal fractionation models. Moreover, the chemical compositions of these enclaves (Table 1) correspond to

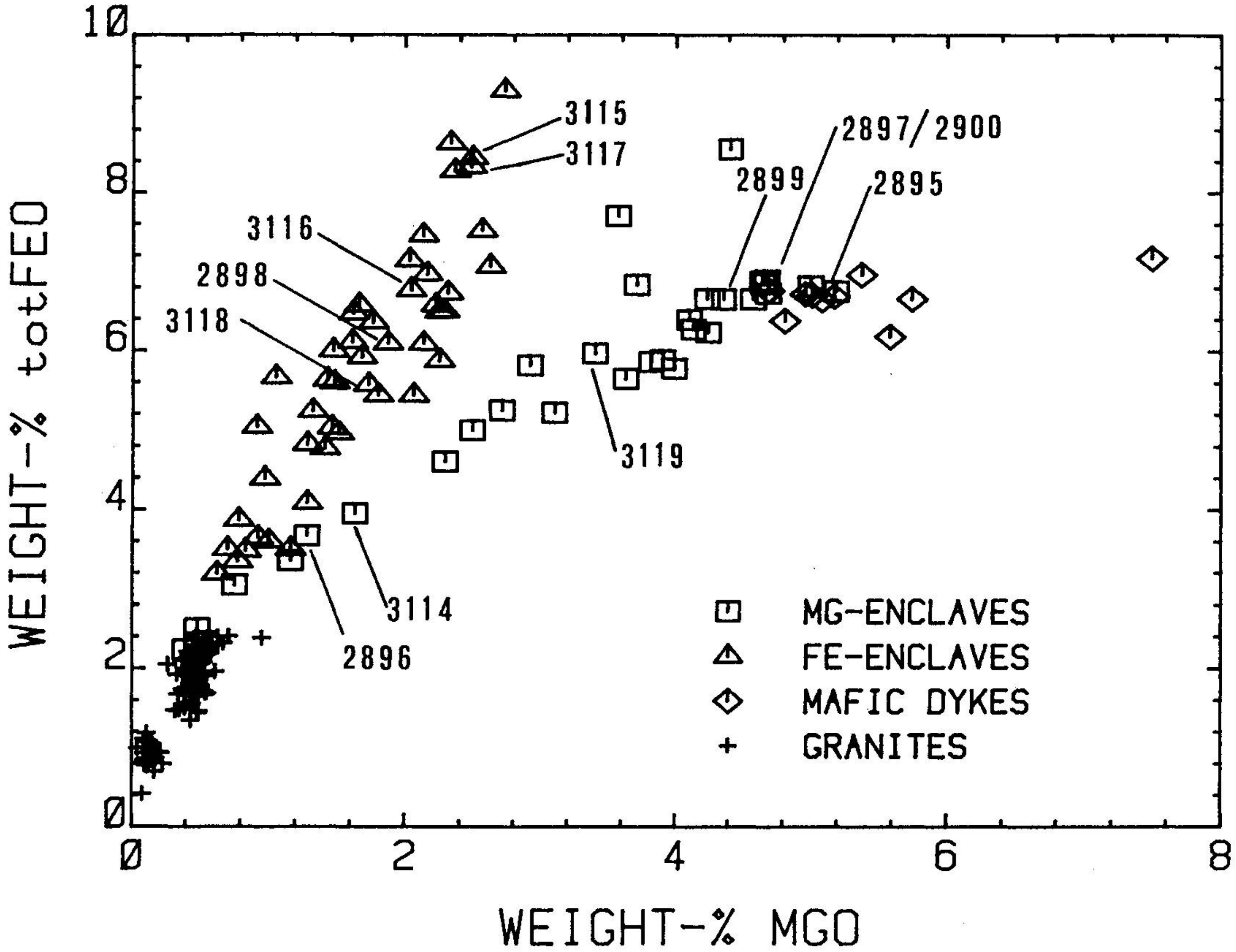

Fig. 3 MgO/totFeO diagram showing the existence of distinct magnesian (with relatively high MgO/totFeO ratio) and ferroan (with lower MgO/totFeO ratio) enclave groups. Data and symbols as in Fig. 2.

none of the classical magma types, in particular in view of their exceptionally high Rb and Zr contents. The origin of these rocks is therefore enigmatic. Their characteristics could be due to:

– early differentiation of the magma responsible for the magnesian enclaves, followed by contamination through mingling and intense late chemical interaction with the granitic magma;

– transformation of magnesian enclaves through the above-mentioned late interaction;

– an independent mechanism, possibly related to partial fusion of basic rocks of the lower crust.

3. Total rock Rb-Sr analyses

3.1. ANALYTICAL PROCEDURE

Six granite and twelve enclave samples have been analysed, the sample size being 30 kg for the granite, 0.5 to 4 kg for the enclaves (description of samples is given in Table 2). The rocks were crushed and milled in agate mills for about 10 to 15 hours in ethanol p.a. Both Rb and Sr analyses were done by isotope dilution. Sr was measured on a single filament multi-collector VG Sector mass spectrometer, Rb on a triple filament AVCO mass spectrometer. The Sr measurement of four granite samples was also performed on the latter machine. Duplicate analyses on both mass spectrometers agree within 0.003% of the measured $^{87}Sr/^{86}Sr$ ratios. The analytical accuracy is 0.003% on the $^{87}Sr/^{86}Sr$ ratio (one sigma standard error of mean) and 1% on the $^{87}Rb/^{86}Sr$. The $^{87}Sr/^{86}Sr$ ratios of the enclaves were routinely determined for better accuracy by unspiked runs.

Analyses of the NBS 987 standard yielded results of 0.71024 ± 0.00006 for the AVCO and 0.71024 ± 0.00001 for the VG Sector mass spectrometer. For age calculation the constants recommended by STEIGER & JÄGER (1977) were used; isochron calculation was performed following YORK (1969) model 1. All age errors are given as two sigma values.

Tab. 2 Sample descriptions. Abbreviations: acc = accessories, all = allanite, ap = apatite, bio = biotite, ep = epidote, hbl = hornblende, kfs = K-feldspar, op = opaques, plag = plagioclase, qtz = quartz, ser = sericite, sph = sphene, xen = xenocrysts, zr = zircon. The coordinates refer to the Swiss topographic grid and the third number indicates elevation. The maps used are sheet n°282 Martigny and sheet n°292 Courmayeur, scale 1:50'000.

KAW	locality	coordinates	rock	type	mineralogical composition
770	Saleinaz	572875/92395/1557	granite	border	overall composition of the border facies:
803	Saleinaz	571415/95885/1538	aplite	border	36% qtz, 24% plag (ser, ep), 37% kfs, 3% bio (chl);
804	Saleinaz	573515/91080/1561	granite	border	acc: zr, ap, sph, all
806	Saleinaz	573235/91710/1559	granite	border	
1908	Argentiere	568000/87090/2950	granite	border	
1909	Argentiere	567250/88260/2870	granite	border	
2895	Charpoua	562715/86225/2990	enclave	Mg	2% xen (qtz, plag, kfs, bio); matrix: plag (ep, ser) 55%, hbl 30%, bio 5-10%, qtz 5%; acc: zr, ap, sph, all, op.
2896	Charpoua	562400/86225/2680	enclave	Mg	20% xen, matrix: plag (altered) 40%, hbl 5%, bio 10%, qtz 15%, kfs 10%; acc: zr, ap, op, all, sph.
2897	Charpoua	562715/86230/2990	enclave	Mg	<<1% xen; matrix: plag (ep, ser) 55%, hbl 30%, bio 5-7%, qtz 5-10%, kfs 1-2%; acc: zr, ap, op, sph
2898	Ecandies	569000/95300/2760	enclave	Fe	no xen; plag (ep, bio) 60%, bio 25%, qtz 15%, acc: zir, ap, op, sph
2899	Charpoua	562700/86210/2980	enclave	Mg	<1% xen; matrix: idem 2897, plag less altered
2900	Charpoua	562710/86225/2990	enclave	Mg	1% xen; matrix: idem 2897, plag fairly altered
3114	Ecandies	569125/95660/2520	enclave	Mg	10% xen; matrix: plag (ep, ser) 40%, hbl 5-10%, bio 5%, qtz 20-25%, kfs 15-20%, acc: zr, ap, op, sph, all
3115	Ecandies	568750/95275/2820	enclave	Fe	1% xen; matrix: plag (ep, bio) 60%, bio 25%, qtz 10%, kfs 2-3%, acc: zr, ap, op, sph
3116	Ecandies	568825/95525/2690	enclave	Fe	1-2% xen; matrix: plag (ep, ser, bio) 60%, bio 10-15%, qtz 20%, sph 1%, acc: ap, zr, op
3117	Ecandies	569000/95300/2750	enclave	Fe	<<1% xen; matrix: idem 3115
3118	Ecandies	568775/95270/2825	enclave	Fe	5% xen; matrix: plag (ep, bio) 60%, bio 20%, qtz 15%, kfs 1-2%, acc: zr, ap, op, sph, all
3119	Charpoua	562450/85825/2700	enclave	Mg	1-2% xen; matrix: plag (ep, ser) 60%, hbl 10%, bio 15%, kfs 2-3%, qtz 10%, acc: zr, ap, op, sph, all

3.2. RESULTS

3.2.1. The Mont-Blanc granite

The samples show a clear regional distribution of their $^{87}Sr/^{86}Sr$- and $^{87}Rb/^{86}Sr$ values, respectively, which can be demonstrated with the strontium evolution diagram (Fig. 4). A first group of rocks comes from the Saleinaz region (Val Ferret, Switzerland): KAW 770, 804 and 806 correspond to samples from the border facies of the granite and KAW 803 to an aplitic dike included in the latter. They have a high $^{87}Rb/^{86}Sr$ ratio, excluding KAW 770. Samples KAW 1908 and 1909 are from the border facies in the neighbourhood of the Tour Noir glacier (Argentière, France); they have rather low $^{87}Rb/^{86}Sr$ ratios around 5. A third group of rocks (KAW 1914 to 1920, MARRO, 1987) comes from the central facies of the granite in the Aiguilles du Tour region (France). Their $^{87}Rb/^{86}Sr$ is between 5 and 10. The following facts are to be noted:

– there is no overall linear pattern of the points, and therefore no isotopic homogeneity at the scale of the massif;

– there is no homogeneity either within the regional groups and even less so, between the two border facies groups (Saleinaz + Argentière);

– samples with high Rb/Sr ratios reveal progressively lower $^{87}Sr/^{86}Sr$ ratios.

A scatter of points similar to that obtained by BAGGIO et al. (1967) therefore emerges, with the difference that these authors analyzed strongly deformed rocks, which are inevitably disturbed isotopically. The seven points of the Aiguilles du Tour group determine a "hyperbole" in the $^{87}Rb/^{86}Sr$ versus $^{87}Sr/^{86}Sr$ diagram (Fig. 4). This has been initially interpreted as the result of partial, parallel remobilization of Rb and Sr through Alpine metamorphism (MARRO, 1987). One may note, however, that only the end points (KAW 1918 and 1920) diverge considerably from a line passing through the five other points. If one accepts as a premise that only KAW 1918 and 1920 have undergone disturbance, mainly loss of Rb, an isochron may be traced which gives 311.6 ± 18.4 Ma (2s) with an initial $^{87}Sr/^{86}Sr$ ratio equal to 0.705 ± 0.002.

Tab. 3 Isotopic data for granite and enclaves of the Mont-Blanc granite.

sample	87 Rb ppm	Sr ppm	87Rb/86Sr	87Sr/86Sr	+/- 1 sigma
KAW 770	74.78	120.73	6.349	0.735620	0.000021
KAW 803	93.50	54.03	17.805	0.773914	0.000019
KAW 804	91.64	41.85	22.569	0.791805	0.000029
KAW 806	79.68	60.93	13.445	0.766827	0.000011
KAW 1908	63.63	121.40	5.370	0.731199	0.000005
KAW 1909	49.47	153.86	3.291	0.719402	0.000009
KAW 2895	49.08	309.08	1.624	0.712578	0.000090
KAW 2896	60.65	198.18	3.132	0.719955	0.000066
KAW 2897	37.24	317.34	1.200	0.710871	0.000026
KAW 2898	108.14	184.61	6.002	0.731287	0.000056
KAW 2899	50.51	305.60	1.690	0.713415	0.000065
KAW 2900	33.92	320.27	1.083	0.710838	0.000081
KAW 3114	61.00	234.18	2.666	0.719104	0.000045
KAW 3115	142.48	139.39	10.482	0.740244	0.000047
KAW 3116	123.56	203.96	6.205	0.728533	0.000047
KAW 3117	136.85	148.43	9.453	0.738546	0.000024
KAW 3118	92.22	167.67	5.634	0.728373	0.000028
KAW 3119	43.98	353.73	1.272	0.712204	0.000196

3.2.2. The mafic microgranular enclaves

In the strontium evolution diagram (Fig. 5), the hornblende-bearing magnesian enclaves plot in a group clearly distinct from the one which corresponds to the biotite-bearing (and amphibole-lacking) ferroan enclaves.

a) The hornblende-biotite magnesian enclaves:
Amongst the analysed samples, KAW 2895, 2896, 2897, 2899, 2900 and 3119 all come from the same locality (Rognon de la Charpoua, Aiguille Verte, east of Chamonix, France). Sample KAW 3114 comes from an outcrop 11 km northeast of the latter (Combe des Ecandies, west of Champex, Switzerland). The enclaves from this second locality are very similar, mineralogically and geochemically, to those from the Charpoua. Even if isotopic evidence confirms this similarity (Fig. 5), we feel that it is reasonable to exclude this sample from the isochron calculation. The six magnesian enclaves define a total rock isochron at 316.1 ± 19.5 Ma (2s) with an initial $^{87}Sr/^{86}Sr$ ratio equal to 0.7058 ± 0.0005. This result is identical within the limits of error, to the age of the granite obtained from the five point array recalculated from data in MARRO (1987).

b) The biotite-bearing ferroan enclaves:
These enclaves (KAW 2898, 3115–3118) also come from a single locality (Combe des Ecandies, west of Champex, Switzerland) and show a degree of scatter in the Sr-evolution diagram, indicating a state of disequilibrium and an apparent age younger than the one mentioned above, with a higher initial $^{87}Sr/^{86}Sr$. Values for the $^{87}Rb/^{86}Sr$ are also distinctly higher, reaching 10.5, which is by far too much for a magma of intermediate composition. The abnormal geochemical character of these rocks is again confirmed by the isotopic data.

4. Interpretation

4.1. GRANITOIDS

The scatter in the Sr-evolution diagram could be due to primary heterogeneity of the magma. In that case, regionally homogeneous sub-systems should produce different sub-isochrons, which is not what one observes, partly through lack of data and partly through subsequent disturbance. It is therefore not possible to conclude on this matter, but it is possible that the border granite, which is

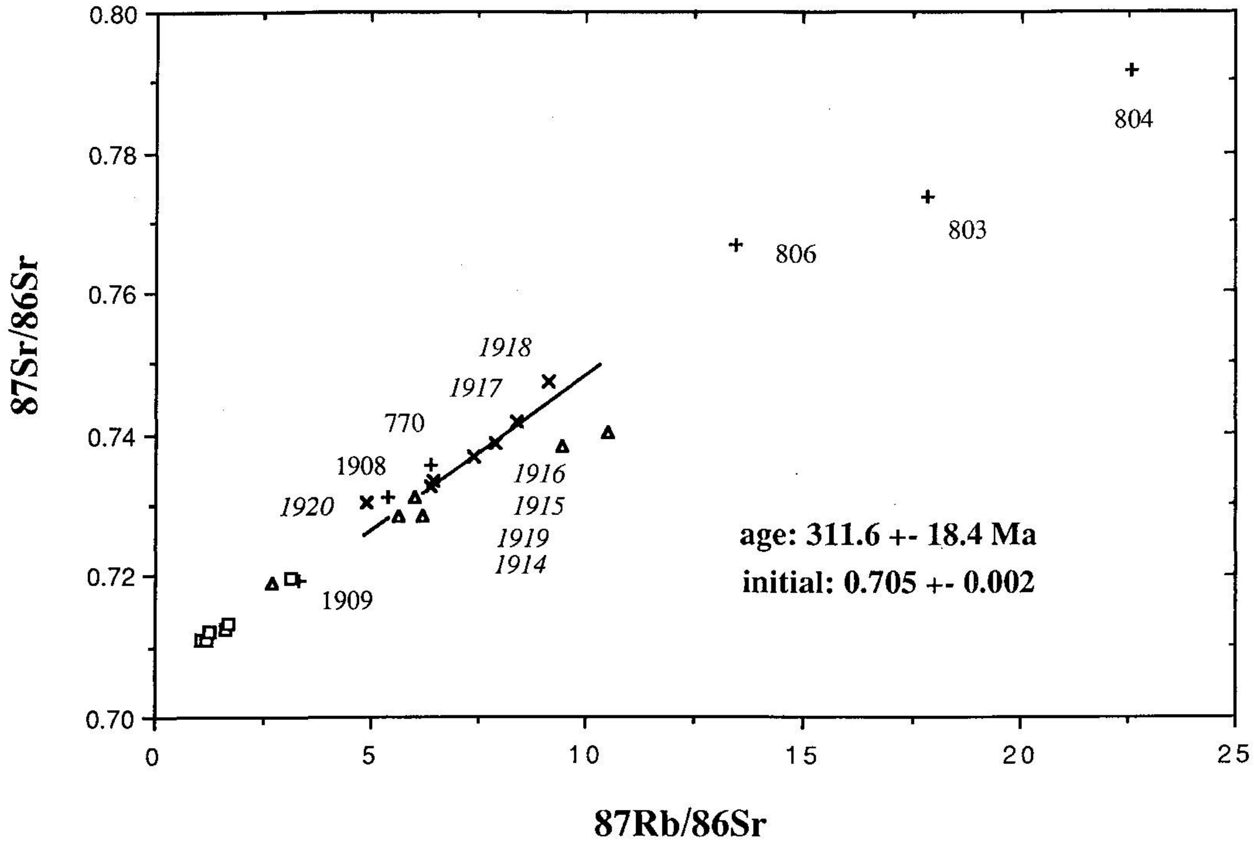

Fig. 4 Sr evolution diagram of both granite and enclave samples. Granite samples are labelled with KAW sample numbers. Symbols as in Fig. 2, with additional diagonal crosses = central facies samples from MARRO (1987), (sample number in italics). For sample numbers of the enclaves, see fig. 5. Isochron of 311.6 Ma is calculated using the five points (KAW 1914-1917, 1919) of MARRO (1987).

geochemically distinct from the central type, was never in isotopic equilibrium with the latter.

Whatever the initial situation, it is clear that one or several episodes of isotopic disturbance have occurred. These are responsible for the common tendency of the samples with high Rb/Sr ratios to have progressively lower $^{87}Sr/^{86}Sr$ ratios. It has been mentioned that early severe deformation affected the granite (BELLIERE, 1987), which could have disturbed the system. The effects of Alpine metamorphism are visible throughout the massif (see 2.2). What then is the significance of the 311.6 ± 18.4 Ma isochron calculated from the five points array (samples KAW 1914-1917 and 1919)? The deliberate exclusion of two points (KAW 1918 and 1920) casts some doubt on the validity of this result, which is, however, comparable with that obtained on the enclaves, within the limits of error. This leads us to reject the possibility of fortuitous alignment through late remobilization. It is possible that this age corresponds to a locally preserved sub-system, but in the final analysis, we prefer to consider the result obtained in the enclaves.

Other linear distributions seem to exist in the Sr-evolution diagram, using points from different regions and of different type, for instance KAW 1920, 1908, 770, 1918, 806 and even enclave 3114, or even all the magnesian enclaves with KAW 1908 and 770. We take them to be purely fortuitous.

4.2. THE MAFIC MICROGRANULAR ENCLAVES

a) The *magnesian enclaves* define an isotopically coherent group. But what is the significance of the calculated age and initial ratio? It is clear that isotopic exchange has occurred between granite and enclaves, already at a stage prior to or synchronous with the formation of the latter, through mechanical mixing between granitic and basic magmas. Mixing has taken place either a) between single acid and basic poles or b) between several variably hybridized acid and basic poles. In both situations, isotopic exchange did not cease after the individualization and rapid chilling of the enclaves. Indeed, if no further exchange had occurred, in case a), the different points should lie on a mixing line in a $1/^{86}Sr$ versus $^{87}Sr/^{86}Sr$ diagram which is not what one sees, and in case b),

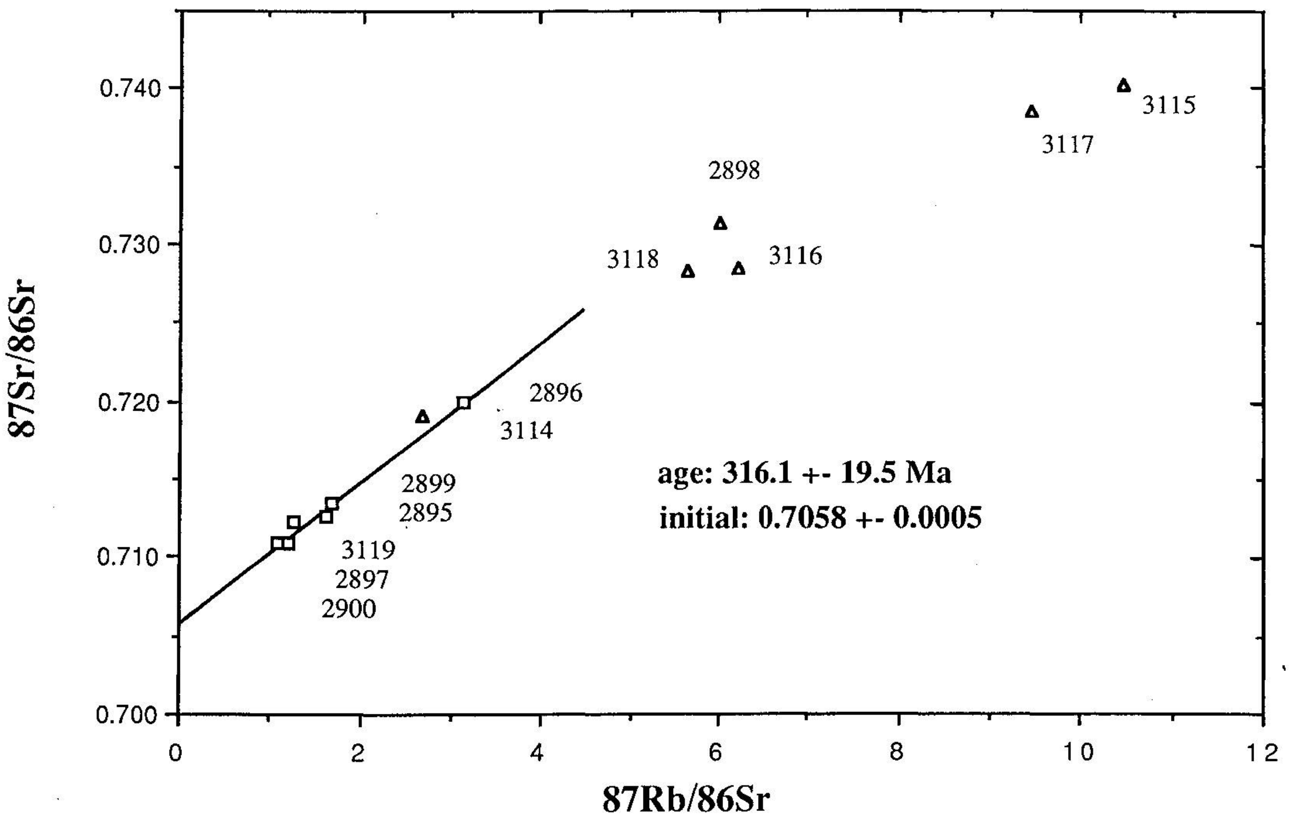

Fig. 5 Sr evolution diagram of enclaves of the Mont-Blanc granite, symbols as in Fig. 2. The errors on the isochron age and the initial ratio of the magnesian enclaves are two sigma values.

the data points should be dispersed in the $^{87}Rb/^{86}Sr$ versus $^{87}Sr/^{86}Sr$ diagram, while in fact they are aligned.

We conclude that total isotopic equilibrium was established between granite and enclaves and that the 316.1 ± 19.5 Ma age result dates precisely this event. This hypothesis best explains the isotopic homogeneity of the enclaves. Such a mechanism has been advocated by Büsch & Otto (1980), Schuler (1983) and Henjes-Kunst et al. (1984), the latter for only part of their enclaves. The following sequence of events is plausible: initiation of exchange between the two systems through mixing in variable proportions, continuation of exchange during solidification of the basic blobs, a small fraction of which probably remains liquid for some time (Büsch & Otto, 1980), and further exchange throughout the span of time during which late magmatic granitic fluids circulate. The enclave system closes when the scale of ionic reactions between rock and fluid phase becomes smaller than the dimensions of the enclaves. The importance of the fluids is underscored by the systematic transformation of hornblende into biotite at the margins of the enclaves and by the absence of dry ferromagnesian phases, such as pyroxenes, generally present in this type of intermediate rock.

If this holds, the $^{87}Sr/^{86}Sr$ ratio of 0.7058 ± 0.0005 would also be valid for the granite. This value is compatible with that of Baggio et al. (1967), whose isochron has been recalculated with new constants, and with that of 0.705 ± 0.002 obtained with the five samples of Marro (1987). These figures are, however, to be considered with caution. Schaltegger (1986), on the other hand, has found an initial ratio of 0.705 for the Central Granite of the Aar massif (another external massif, Central Alps, Switzerland), whose calc-alkaline character and geotectonic setting show it to be very similar to the Mont-Blanc granite. We conclude that the value of 0.7058 derived from the enclaves may be extended to the whole system.

The isotopic system of the magnesian enclaves is more homogeneous than that of the host granite. It is likely that these rocks have been preserved from remobilization during Alpine metamorphism. The fresh state of different minerals (calcic plagioclase not transformed to saussurite, brown biotite) relative to those of the granite is a good indication in this respect. From this point of view, the isotopic system of these enclaves may be considered to be an undisturbed relic of the original granite-enclaves system.

b) The *ferroan enclaves* form an isotopically heterogeneous group, in spite of the fact that the samples all come from the same locality. No matter what their origin, their small size suggests equilibrium with the host granite at the end of the magmatic stage, as for the magnesian enclaves. It is a late event which is responsible for the scatter of points in the Sr-evolution diagram. This event could be late- to post-magmatic retrogression (endometasomatosis) through the action of hydrothermal fluids, but is assumed to be due to Alpine metamorphism, as suggested by the greenish colour of the biotites. It may be questioned why only one of the two groups of enclaves underwent these modifications. It is proposed that their smaller size and distinctly higher biotite content rendered the ferroan enclaves more sensitive than the others to phenomena involving remobilization, of radiogenic Sr in particular.

In any case, the analyses of the ferroan enclaves cannot be interpreted in terms of age. As for their very high $^{87}Rb/^{86}Sr$ ratios, they imply intervention of an important crustal component, either at the site of origin of the basic material or, at a later stage, through strong chemical interaction between enclaves and host granitic magma. These isotopic data do not therefore afford further criteria for the determination of the ultimate source of this material.

5. Conclusion

The Mont-Blanc granite is an isotopic system partially remobilized during Alpine orogenesis and possibly prior to this event. The large magnesian enclaves of the granite, originally in isotopic equilibrium with the latter, have been preserved from remobilization and give an age of 316.1 ± 19.5 Ma and an initial $^{87}Sr/^{86}Sr$ ratio of 0.7058 ± 0.0005 for the system. These results do not lead to a conclusion on the magmatic or non-magmatic origin of the enclaves. One can only say that equilibrium existed between them and the granite, a state to which the existence of a liquid phase within the enclaves no doubt contributed.

The distinction between magnesian and ferroan enclaves is also apparent on the isotopic level; the latter form a heterogeneous group which has probably undergone remobilization.

The age of 316.1 ± 19.5 Ma places the Mont-Blanc granite in a late-Hercynian phase of intense magmatic activity and granite intrusion. Virtually all the nearby Hercynian massifs include calc-alkaline bodies of Westphalian age: eastern Massif Central, Vosges, external Alpine massifs (LAMEYRE & AUTRAN, 1980; TRÜMPY, 1980), Black-Forest (EMMERMANN, 1977). Several have a potassic tendency like the Mont-Blanc; they are due no doubt to some single geotectonic event involving similar magmatic sources. In this respect, the $^{87}Sr/^{86}Sr$ initial ratio of 0.7058 excludes a source of metasedimentary mid-crustal type. It indicates rather fusion of lower crust with probable mantle contributions in unknown proportions. As for the independent basic magma, the source of the magnesian enclaves, its $^{87}Sr/^{86}Sr$ initial ratio has been modified through mixing and equilibration with the granite. It should have been originally lower, very likely with mantle values.

Acknowledgments

We would like to thank our colleagues of the Universities of Fribourg, Lausanne and Berne - Abteilung für Isotopengeologie, for help and advice in the laboratory. We are particularly grateful to S. Ayrton, M. Flisch, R. Hänny and E. Jäger for constructive review of earlier versions, and especially to S. Ayrton for the english version of the manuscript. The work of U.S. was supported by the Schweizerischer Nationalfonds zur Förderung der wissenschaftlichen Forschung.

References

BAGGIO, P., FERRARA, G. and MALARODA, R. (1967): Results of some Rb/Sr age determinations of the Rocks of the Mont Blanc Tunnel. Boll. Soc. Geol. Ital. 86, 193-212.

BELLIERE, J. (1987): The Deformation History of the Mont Blanc-Massif. Terra Cognita 7/2-3, 88.

BÜSCH, W. und OTTO, J. (1980): Endogenetic Inclusions in Granites of the Black Forest, Germany. N. Jb. Mineral. Mh., H.6, 269-282.

BUSSY, F. (1987): Echanges minéralogiques et chimiques entre un magma acide et un magma basique coexistants dans le granite du Mont-Blanc, implications et limites pour un modèle pétrogénétique. Schweiz. Mineral. Petrogr. Mitt. 67/3, 380-384.

DIDIER, J. (1973): Granites and their Enclaves. Elsevier, Amsterdam.

EMMERMANN, R. (1977): A Petrogenetic Model for the Origin and Evolution of the Hercynian Granite Series of the Schwarzwald. N. Jb. Mineral. Abh. 128/3: 219-253.

HENJES-KUNST, F., ALTHERR, R. und OTTO, J. (1984): Zur Genese von endogenen Einschlüssen in I-Typ-Granitoiden: Argumente aus Sr-Isotopen-untersuchungen. Fortschr. Mineral. 62/1, 87-89.

JACQUEMIN, CH. et BELLIERE, A. (1984): Origine magmatique des enclaves du granite du Mont Blanc. Schweiz. Mineral. Petrogr. Mitt. 64/3, 373-388.

LAMEYRE, J. et AUTRAN, A. (1980): Les granitoïdes de France. Mém. Bur. Rech. Géol. Min. 107, 51-97.

LA ROCHE, H., LETERRIER, J., GRANDCLAUDE, P. and MARCHAL, M. (1980): A classification of volcanic and plutonic rocks using R1-R2 diagram and major ele-

ment analysis. Its relationship with current nomenclature. Chem. Geol. 29, 183-210.
MARRO, CH. (1987): Histoire des granitoïdes du Mont Blanc en Suisse. Bull. Soc. Frib. Sci. Nat. 76, 73-128.
POTY, B.P., STALDER, H.A. and WEISBROD, A.M. (1974): Fluid Inclusions Studies in Quartz from Fissures of Western and Central Alps. Schweiz. Mineral. Petrogr. Mitt. 54/2-3, 717-752.
SCHALTEGGER, U. (1986): Geochemie und Rb-Sr-Systematik der Aarmassiv-Granite zwischen Grimsel und Reusstal. Schweiz. Mineral. Petrogr. Mitt. 66/3, 462-466.
SCHULER, CH. (1983): Die interne Sr-Isotopensystematik des herzynischen Albtalgranits (Schwarzwald). Diss. ETH-Zürich, 187 pp. Unpubl.
STEIGER, R.H. and JÄGER E. (1977): Convention on the use of decay constants in geo- and cosmochronology. Earth Planet. Sci. Lett. 36, 359-363.
STRECKEISEN, A. (1981): Provisional Remarks on Chemical Classifications. IUGS Subc. Igneous Rocks, Circ. 34, Contr. 90.
TRÜMPY, R. (1980): Geology of Switzerland, a guidebook. Part A: An Outline of the Geology of Switzerland. Schweizerische Geologische Kommission (Ed.), Wepf, Basel, New York.
VERNON, R.H. (1983): Restite, Xenoliths and Microgranitoid Enclaves in Granites. J. and Proc. Roy Soc. New South Wales 116, 77-103.
VON RAUMER, J. (1969): Stilpnomelan als alpin-metamorphes Produkt im Mont Blanc-Granit. Contrib. Mineral. Petrol. 21, 257-271.
VON RAUMER, J. (1974): Zur Metamorphose amphibolitischer Gesteine im Altkristallin des Mont Blanc- und Aiguilles Rouges-Massivs. Schweiz. Mineral. Petrogr. Mitt. 54/2-3, 471-488.
VON RAUMER, J. (1984): The external Massifs, relics of Variscan Basement in the Alps. Geol. Rund. 73/1, 1-31.
WYLLIE, P.J., COX, K.G. and BIGGAR, G.M. (1962): The Habit of Apatite in Synthetic Systems and Igneous Rocks. J. Petrol. 3/2, 238-243.
YORK, D. (1969): Least Squares fitting of a straight line with correlated errors. Earth. Planet. Sci. Lett. 5, 320-324.

Manuscript received October 10, 1988; with minor revisions accepted October 24, 1988.