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Petrography and geochemistry of the Vallorcine granite (Aiguilles Rouges massif, Western Alps)

by P. Brändlein¹, G. Nollau¹, Z. Sharp² and J. von Raumer³

Abstract

The pre-Mesozoic basement of the Aiguilles Rouges massif (Western Alps) was intruded, during Late Variscan time, by the Vallorcine granite, and its emplacement was accompanied by strike slip tectonics. In the main granite body, about 15 km long, a lower, more coarse grained porphyritic granite can be differentiated from the main, less coarse grained porphyritic granite of the upper levels. Major and trace elements indicate a differentiation sequence from early leucogranites to the porphyritic granites (lower and upper facies), followed by granite porphyries and rhyolites. The main facies corresponds to an S-type granite, confirmed by stable isotopes, zircon morphology and the presence of the Al-rich phases like muscovite, cordierite, andalusite, and sillimanite. After fusion under low water activities, the magmatic ascent occurred at adiabatic conditions and was followed, during the cooling stage, by internal differentiation. Stable isotopes and the presence of topaz and tourmaline indicate the existence of a limited hydrothermal late stage at lower temperatures.

Keywords: S-type granite, geochemistry, stable isotopes, Variscan, Vallorcine granite, Western Alps.

1. Introduction

The Vallorcine granite, a narrow approximately 15 km-long and 1 km-wide rock unit, extends from Miéville in the Rhone Valley in southeastern direction to the Col de Montets (Fig. 1). The first description of the granite was published by NECKER (1822), and more detailed papers were provided by MEYER (1917), REINHARD and PREISWERK (1927) and COLLET et al. (1952).

The Variscan basement of the Aiguilles Rouges, which the granite intruded, and the mylonites related to the granite were investigated by VON RAUMER (1984 a, b, 1987) and JOYE (1989). The Vallorcine granite represents an important Late Variscan magmatic and tectonic event in the Alpine basement which may be comparable to those observed outside the Alps. Under this point of view, a research on the petrographical and geochemical characteristics of the Vallorcine granite was obviously needed.

2. Geology

The country rocks of the Vallorcine granite, the Variscan basement of the Aiguilles Rouges massif, are part of the External Massifs of the Alps and have been assigned to the crustal segment of the Moldanubian zone of the Variscan framework outside the Alps.

According to VON RAUMER et al. (1993), pre- and early-Palaeozoic sediments and interbedded magmatic rocks were penetrated discordantly by Ordovician-Silurian granitoids. Eclogites of Silurian-Devonian age (PAQUETTE et al., 1989) and the metasedimentary framework experienced a Barrovian type metamorphism (probably Devonian age; JOYE, 1989; VON RAUMER et al., 1993) from kyanite- to sillimanite-biotite ± garnet-bearing mineral assemblages. Evidence for the late thermal history is particularly abundant in the area next to the granite. The Vallorcine granite intruded along a fractured mylonite-zone (JOYE,

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AIGUILLES ROUGES - MONT BLANC
Geological Map

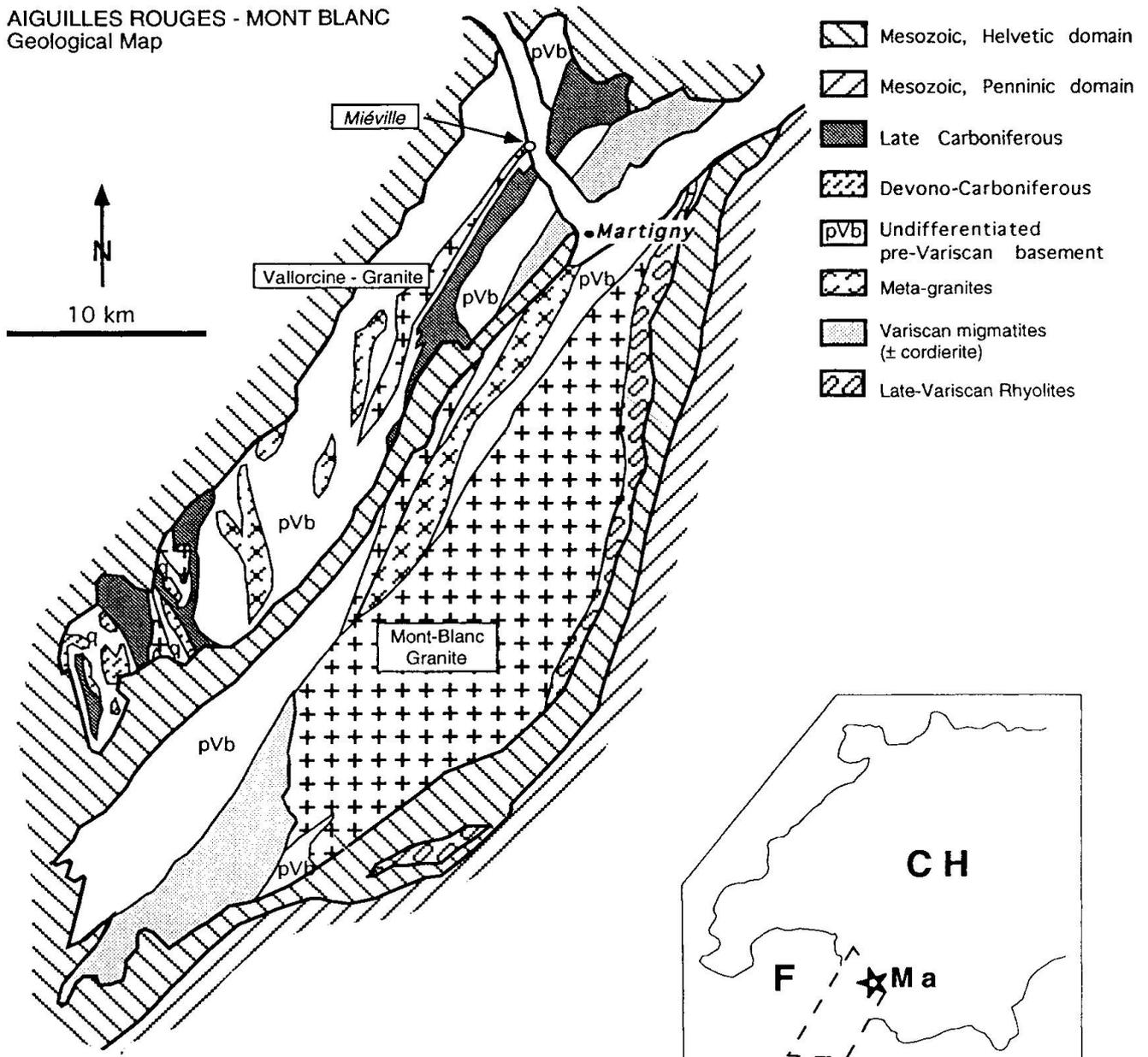


Fig. 1 Geographical situation of the investigated area, located at the France-Switzerland border (Ma: Martigny), and geological framework of the Vallorcine granite.

1989) with complex fold structures that were superimposed by a steeply dipping dextral shear-zone. Crystallization of parageneses with cordierite and sillimanite were reported from specific shear-planes. Dating (Rb-Sr "thin-slab" method; THÖNI, 1989 in JOYE, 1989) suggests that the metamorphism occurred around 370 Ma and cooling in the shear-zone below 500 °C around 300 Ma ago. The Vallorcine granite was emplaced during this time interval and may have a comparable age to that of the Montenvers granite in the adjacent Mont Blanc area (\pm 307 Ma, U/Pb zircon, BUSSY and VON RAUMER, 1993). JOYE (1989) confirmed the existence of discordant contacts on the northern side of the granite body, and the occurrence of

recrystallized quartz in the country-rocks indicates slight contact metamorphism. The wide contact zone discussed by REINHARD and PREISWERK (1927) is reinterpreted as a pre-granitic, fine-grained fractured mylonite-zone. Also the SE-contact is heavily mylonitized (STECK and VOCAT, 1973; KERRICH et al., 1980), and the manifestation of late-Variscan and Alpine tectonics therein seems probable.

The Alpine overprint reached the lowest metamorphic grade of the greenschist-facies (VON RAUMER, 1971, 1984; PILLOUD, 1990), and a shortening of 30% of the steep to the SE dipping strain ellipsoid is possible (VON RAUMER, 1987).

Tab. 1 Indication of rock-types and numbers used in the different illustrations (coordinate grid after Schweiz. Landeskarte).

No.	Coordinates	Rock-type
1b	568 250/110 950	porphyritic granite D ¹⁾
4	567 300/109 910	porphyritic granite D
22	562 560/102 400	porphyritic granite H ²⁾
34	562 440/102 820	porphyritic granite H
74	561 470/102 080	porphyritic granite H
154	561 530/ 99 240	porphyritic granite H
168	561 420/100 050	porphyritic granite H
1a	568 250/110 950	leucogranite
1c1	568 250/110 950	leucogranite
122	564 810/106 700	granite porphyry
1466	563 575/108 660	rhyolite
210	558 990/ 94 100	rhyolite
119/1	566 200/107 760	aplite
4/1	567 300/109 910	autolith
187/A	568 150/110 950	autolith

¹⁾ D: porphyritic granite of lower levels;

²⁾ H: porphyritic granite of upper levels.

3. Petrography

Based on the reevaluation of BRÄNDLEIN (1991), an early, cordierite-bearing leucogranite, a porphyritic and aplitic granite, dyke rocks (granite-porphyry, rhyolite, lamprophyre) and different auto- and xenoliths are distinguishable (see Tab. 1 for rock samples).

3.1. PORPHYRITIC GRANITE

The most abundant rock is a porphyritic, coarse-grained granite which, from a morphological-geographical standpoint, can be divided in a "low" (called "Miéville-type", outcrop areas between Miéville–Van d'en Bas) and a "high" or normal facies (all higher areas between Van d'en Bas and Col de Montets, more than 90% of the entire granite body).

The *Miéville-type* (type locality quarry Miéville, Coord.: 110.9 / 568.25) shows large, oriented K-feldspar crystals in a relatively biotite-rich ground mass, while the *normal granite* (type locality road Finhaut–Emosson, Coord.: 102.8 / 568.25) shows a somewhat finer grain size and contains less biotite. Autoliths and xenoliths are found mostly in the Miéville-type granite. Major constituents of the porphyritic granite are K-feldspar (orthoclase, microcline), plagioclase, quartz, biotite with zircon, altered garnet and some apatite.

K-feldspar shows two magmatic growth stages: (i) a first hypidiomorphic to idiomorphic stage as up to 6 cm-long phenocrysts and (ii) a second as small xenomorphic groundmass crystals. The phenocrysts display Karlsbad twin and perthitic to microperthitic unmixing features. Idiomorphic plagioclase, biotite, apatite and quartz as rounded, clear drops or in hexagonal high-temperature habit are frequent inclusions, which form often a synneutic structure. It demonstrates the crystallization sequence in the granite, because the innermost inclusions are idiomorphic plagioclase crystals with the same An value as the core of the "free" plagioclase, which again is followed by biotite, apatite and quartz. Some zoned K-feldspar crystals contain a rounded core, and lobated cores are interpreted to represent corroded relics of an earlier generation. Alteration products of K-feldspar are kaolinite and sericite.

Plagioclase (< 4 cm), mostly twinned and oscillatory zoned (An₂₉₋₁₂), exists as idiomorphic phenocrysts or as xenomorphic groundmass crystals. Some few phenocrysts show patchy zoning with a corroded core, the latter representing an older generation of plagioclase. Sericitization, propylitization and saussuritization are common alterations.

Biotite (< 2 cm), light brown to reddish brown reveals a tabular, flaky habit. Inclusions are small zircon, chloritized garnet and apatite. Alteration is shown by unmixing of titanium (sagenite lattice) and chloritization.

Quartz (< 0,8 cm) is in most cases anhedral and cloudy, and contains many fluid inclusions. Locally fractures are healed by oriented quartz grains.

Muscovite I (\pm 1 cm) is a tabular magmatic generation having occasionally an oriented intergrowth but is mostly chloritized (biotite remaining unaffected). Minor constituents are idiomorphic, short columnar, pink andalusite, topaz, zircon, some tourmaline and three different generations of apatite. An early, restitic one is rounded, sometimes broken without any inclusions, whereas the following magmatic apatite I displays an euhedral habit and contains other minerals as inclusions. Fine, needle-shaped magmatic apatite II intersects all other minerals without any orientation. As products of a late magmatic or post-magmatic alteration, chlorite, titanite, epidote and two more generations of white mica are observed. White mica II appears as sericite in andalusite and feldspar, and white mica III overgrows locally all other minerals forming radial aggregates and being probably related to a late pneumatolytic stage.

3.2. APLITIC GRANITE

A *marginal facies* of even-grained, *aplitic granite* can sometimes be found (type locality above Finhaut, Coord.: 104.9 / 563.55). Its major constituents are K-feldspar (perthitic microcline), almost pure albite, quartz and occasionally biotite. Minor constituents are garnet (mostly chloritized) and fine aggregates of light mica (pinite), presumably altered cordierite, as well as felty aggregates of light micas and sillimanite (fibrolite). Accessory apatite, zircon, epidote, rutile, hematite and pyrite are present.

3.3. PINITE-BEARING LEUCOGRANITE

A separate variety is a pinite-(cordierite-)bearing leucogranite, which is found at lower levels of the granite body (type locality quarry Miéville, coord.: 110.9 / 568.25). It is distinguished by its bright white colour and its mostly elongated, light green aggregates of pinite. As the parallel structure of this rock is cut discordantly by the not structured porphyritic granite the leuco-granite should be a precursor of the porphyritic granite. Microscopically it shows a clearly visible, mylonitic overprint and, consequently, the major constituents K-feldspar, plagioclase and quartz appear strongly recrystallized. Large crystals are broken and rotated, and fissures are filled with a fine-grained recrystallized quartz-feldspar mixture. The elongated pinite spots are the alteration product of former cordierite, and additional relics of pink andalusite can be seen. Accessory biotite, apatite, zircon as well as rutile, titanite, hematite and epidote are found.

3.4. SUBSEQUENT DYKES

In addition to these three types, granite-porphyry (type locality entry to Vallon d'Emaney, Coord.: 106.7 / 564.8), aplite (type locality above Col des Montets, Coord.: 558.5 / 94.5) and rhyolite (type locality near Barrage d'Emosson, Coord.: 561.3 / 101.75) cut discordantly the granite and the wall rocks.

The rare, nearly vertical cutting granite-porphyry dykes reach up to 100 m length with 1–2 m width. Even macroscopically they show an injection texture made visible by the orientation of large K-feldspar and plagioclase phenocrysts. Microscopically the idiomorphic, zoned K-feldspars (< 3 cm) show perthitic unmixing and Karlsbad twinning. Plagioclase (< 2 cm) is twinned according to the albite or pericline law. Due to later

metasomatism it is replaced mostly by albite and, to less extent, by sericite and calcite. Quartz (< 1 cm) has a dihexagonal "high-temperature" habit. Corrosion led to rounded grains. Tabular, white and dark micas are uncommon and are almost completely hydrothermally altered. The fine ground mass crystals of K-feldspar, plagioclase, quartz, white and dark mica, apatite, garnet, zircon and tourmaline exhibit flowage structures around the phenocrysts without any sign of deformation or recrystallization.

Aplite dykes (dm-m) are rarely cutting through the granite, but are abundant at the SW-corner of the granite, where they form a network within the wall rocks. Tourmaline, white mica and quartz display a zoned structure of the aplitic veins. Hypidiomorphic K-feldspar (orthoclase and microcline) displays Karlsbad twinning, perthitic unmixing, and encloses plagioclase and secondary albite. Plagioclase, mostly albite, is twinned and shows myrmekitic grain boundaries with quartz. Tabular, primary white mica has grown parallel to the direction of injection. Secondary, hydrothermal micas have a small, laminar habit. Clear and completely recrystallized quartz shows curved grain boundaries. Hypidiomorphic, orange-red pleochroitic andalusite with clearly visible (110) cleavage has sometimes alteration rims or is pseudomorphosed by sericite. Tourmaline presents brown to green or a zonal blue (core) to green (rim) pleochroism and triplets. Accessory minerals are rutile-titanite, hematite, garnet and apatite.

The granite body and its country-rocks are also cut by dykes of grey rhyolitic rocks which may show a complete transition, e.g. gradation in colour, composition and texture (vitreous chilled margins to porphyritic) from granite-porphyry to rhyolite. Laminar, idiomorphic to hypidiomorphic K-feldspar (perthitic orthoclase or microcline) grew sometime zonal, or as Karlsbad-twins and cross penetrating twins. Hypidiomorphic plagioclase is twinned according to the albite and pericline laws, and almost completely replaced by sericite. Clear quartz is idiomorphic to hypidiomorphic, some grains with corroded grain boundaries, some with "high temperature" habit. Accessories are apatite, titanite, rutile, garnet, zircon and opaques.

3.5. AUTOLITHS AND XENOLITHS

Well rounded inclusions (no chilled margins) with an unoriented texture, are interpreted as autoliths and are found in the Miéville-type of the porphyritic granite. They are mostly fine-grained, bi-

otite-rich, and contain plagioclase, K-feldspar, quartz and few crystals of strongly altered amphibole. Two generations of apatite are observed, a fine needle shaped and a short, coarse one.

Xenoliths represent the wall-rocks of the granite at surface and subsurface levels, indicating the intrusive character of the Vallorcine granite. Five types have been distinguished:

- a white mylonite-xenolith (JOYE, 1989) with some recrystallization and new growth of albite and quartz;
- white leucogranite xenoliths with dark patches of pinitite, replacing cordierite;
- dark gneiss xenoliths with protomylonitic texture, dark bands with biotite and chlorite, clear bands composed of quartz and feldspar;
- normal gneiss xenoliths with fibrolitic sillimanite in biotite;
- restitic xenoliths with large biotite flakes and fibrous mats of sillimanite. Yellow sericite spots may have been cordierite or andalusite.

Because of the difficulty in accurately determining modal analyses in coarse grained rocks with a fine grained groundmass, it was advantageous to plot all modal values expressed as meso-norm minerals (MIELKE and WINKLER, 1979).

4. Zircon morphology

The abundance of zircon decreases from the porphyritic granite to the even grained granites, the leucogranite and the granite porphyry, while no zircon was found in the rhyolites. Many of the zircons are clear and idiomorphic, but reddish to brown coloured grains are also present. As inclusions clear hollow spaces and apatite were observed. Some idiomorphic zircons are zoned and display rounded cores. Partial overgrowths by hydrozircon can be seen.

The crystal morphologies define typical evolutionary trends TET (PUPIN, 1980, 1988) with a relatively uniform distribution pattern for all granite types. Noticeable is the relatively irregular jagged trend which, for short, is not illustrated, but indicates different source rocks. Zircon populations with habits corresponding to the high temperature field after PUPIN (1980) have no recognizable core nor zonation. The presence of zircons with the only prism face (100), in which the pyramid faces (101) and (211) are roughly equally developed, might demonstrate, after PUPIN (1980, 1988), unusual high formation temperatures and water undersaturated "dry" melting conditions. Such morphologies are also explained by the chemical composition of the magma and the related structural and chemical implications

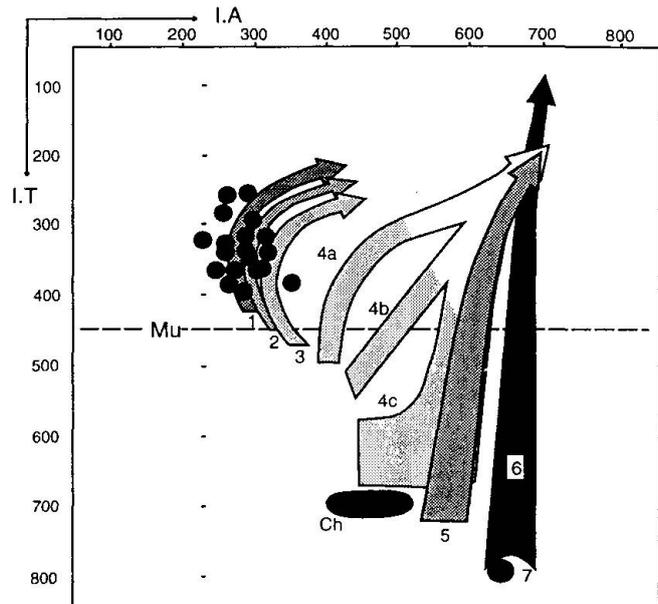


Fig. 2 Zircon population diagram (PUPIN, 1980, 1988) pleading for the anatectic and intrusive character of the Vallorcine granite.

on the growth of the zircon crystals (BENISEK and FINGER, 1993). Trends with both start and end maxima may be the consequence of heterogeneous source rocks leading to contrasting chemical compositions in the magma. The evolutionary trends of zircon in all these rocks can be ascribed to declining temperatures in peraluminous melts indicating an anatectic origin. A clear picture is drawn by the distribution of the main population points (AT) in the typological diagram (Fig. 2), as all rock types plot in the fields 2 and 3 i.e. anatectic, intrusive granites.

Based on zircon morphology (PUPIN, 1980), the Vallorcine granite is classified as a differentiated, anatectic granite from heterogeneous source-rocks.

5. Mineral chemistry

Electron microprobe analysis were performed at Bern University with an ARL-SEMQ Microprobe (15 kV, 20 nA). After correction of the oxide values for absorption, fluorescence and atomic number the stoichiometric compositions were calculated (programs EMMA 5.1 and NORM, Bern University).

Biotite, the only mafic mineral, is relatively rich in siderophyllite (Tab. 2a, Fig. 3). The composition for the biotite in the porphyry granite changes only in a small range (Al^{IV} : 2.45–2.64; $Fe / Fe + Mg$: 0.6–0.7). Biotite Al^{IV} -values form a con-

Tab. 2a Chemical composition of biotites.

Sample	Porphyritic granites								Autolith	Aplite
	D ¹⁾		H ²⁾		H		H			
	1b		52		110		112		115	
SiO ₂	35.62	35.37	34.88	35.17	35.3	35.64	35.04	35.46	35.53	32.61
TiO ₂	3.79	3.61	2.8	2.57	1.99	3.58	2.51	2.76	4.23	1.74
Al ₂ O ₃	16.99	17.74	19.33	18.86	17.99	18.87	18.3	19.04	17.23	17.7
FeO _{tot}	22.57	22.36	23.43	23.69	22.96	22.05	23.37	21.85	22.73	29.86
MnO	0.22	0.18	0.31	0.28	0.25	0.3	0.22	0.27	0.2	0.13
MgO	6.72	6.05	5.47	4.58	5.97	6.15	5.22	5.23	5.81	2.85
Na ₂ O	0.14	0.11	0.11	0.09	30.15	0.16	0.13	0.07	0.11	0.03
K ₂ O	9.93	9.53	9.67	9.59	10.02	9.92	9.8	9.81	9.5	8.38
Total	95.98	94.95	96	94.83	94.64	96.68	94.59	94.49	95.34	93.29
Cations calculated for 22 O, all Fe = Fe ²⁺										
Si	5.4987	5.4962	5.3878	5.5022	5.5366	5.431	5.5027	5.5193	5.5092	5.361
Ti	0.4403	0.4224	0.3253	0.3019	0.2346	0.41	0.296	0.3229	0.4929	0.2146
Al	3.0907	3.2489	3.519	3.477	3.3267	3.3894	3.3868	3.492	3.1484	3.4297
Fe	2.9134	2.9056	3.026	3.0987	3.0119	2.8097	3.069	2.8439	2.9476	4.1051
Mn	0.0291	0.0239	0.041	0.0368	0.0338	0.0386	0.0286	0.0358	0.0264	0.018
Mg	1.5459	1.4	1.2594	1.0687	1.3966	1.3977	1.2226	1.2129	1.3422	0.6982
Na	0.0405	0.032	0.0326	0.0279	0.0461	0.047	0.0404	0.0215	0.0345	0.0087
K	1.9544	1.8883	1.9051	1.914	2.0045	1.9288	1.964	1.9486	1.8792	1.7573

Tab. 2b Chemical composition of muscovites.

Sample	Porphyritic granites						Aplite	Auto-lith	Granite Porphyry	Rhyolite
	D ¹⁾	H ²⁾	H	H	H	H				
	188	52	66	110	112	193	104/1	4/2	122	80/1
SiO ₂	43.81	50.68	48.77	47.5	46.09	42.78	46.85	45.63	45.97	46.4
TiO ₂	0.08	0.	0.1	0.48	0.29	0.14	0.28	0	0.42	0.08
Al ₂ O ₃	15.94	32.49	34.39	26.69	36.13	24.48	35.54	29.64	35.45	29.41
FeO	13.87	1.21	1.66	5.29	1.11	14.16	2.29	6.34	1.69	6.44
MnO	0.81	0	0.04	0.06	0	0.1	0.03	0.06	0	0.21
MgO	6.37	0.8	0.74	3.21	0.54	1.79	0.31	3.07	0.48	1.46
Na ₂ O	0	0.2	0.29	0.09	0.61	0	0.61	0.1	0.63	0.09
K ₂ O	9.65	10.67	10.27	9.16	10.43	10.22	10.3	10.09	8.45	9.86
Total	90.53	96.06	96.26	92.47	95.19	93.68	96.2	94.94	93.08	93.95
Cations calculated for 22 O										
Si	6.7	6.6365	6.3931	6.6103	6.1281	6.2674	6.1899	6.2688	6.1908	6.4191
Ti	0.0091	0	0.0103	0.0503	0.0285	0.0156	0.0274	0	0.0422	0.0088
Al	2.8723	5.0144	5.3199	4.3774	5.6624	4.2272	5.5343	4.8002	5.6264	4.7949
Fe ²⁺	1.7742	0.1326	0.1818	0.6154	0.1234	1.7349	0.2532	0.7287	0.1901	0.7445
Mn	0.1049	0	0.0045	0.0066	0	0.0122	0.0035	0.0074	0	0.0243
Mg	1.453	0.1556	0.1445	0.6656	0.1066	0.3909	0.062	0.6281	0.0962	0.3014
Na	0	0.0518	0.0726	0.0248	0.1566	0	0.155	0.0266	0.1648	0.023
K	1.8828	1.7829	1.7163	1.6253	1.7698	1.9107	1.7353	1.7692	1.4517	1.7403
Al ^{VI}	1.57	3.65	3.71	2.99	3.79	2.49	3.72	3.07	3.82	3.21
Mg/Mg+Fe	0.54	0.44	0.52	0.46	0.18	0.20	0.46	0.34	0.29	

¹⁾ D: porphyritic granite of lower levels; ²⁾ H: porphyritic granite of upper levels.

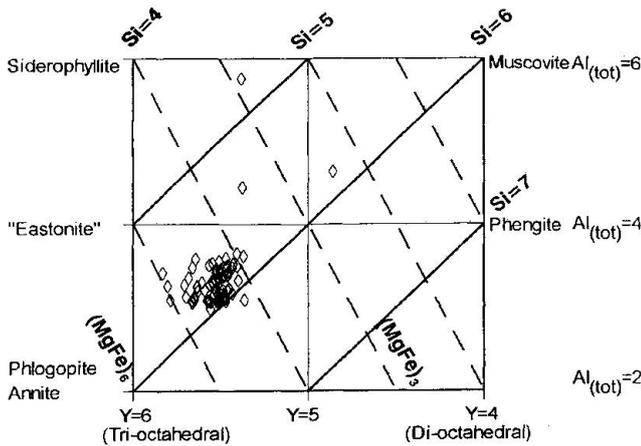


Fig. 3 Composition of biotites from the different granitoid rocks (plot after DEER *et al.*, 1992), same signature for biotites from all rock types (for values see Tab. 2).

tinuum from low values in the autoliths to higher Al^{IV} -values in the leucocratic rocks by approximately constant $Fe / Fe + Mg$ values (Fig. 3).

White mica (Tab. 2b) displays two evolutionary trends in all rocks, an obvious increase of celadonite component with decreasing Al^{IV} content and an increase of Mg with slightly decreasing Al^{IV} content.

Plagioclase. The anorthite content varies between An_{40} and albite for the different rocks. Only plagioclase of the leucogranite consists of 90% albite. Mapping of plagioclase crystals with oscillatory zoning demonstrates a continuous decrease of anorthite-content to the rim (core An_{29} , rim An_{12}).

K-feldspar is poorly zoned, and Ba shows no systematic distribution nor specific enrichment. Ba might have been enriched already in early biotite, but the lack of corresponding analysis does not allow any precision. Or-rich phenocrysts with Ab-rich lamellae caused by subsolidus exsolution are recognizable.

Garnet appears sporadically, but chloritization did not allow any analysis.

The pink coloured *andalusite* shows slight incorporation of Fe, Mn (appr. 1 mol%), and the trace-elements in sillimanite are still lower.

Cordierite is replaced by pseudomorphs of very fine grained chlorite and white mica (pinite), and the high Fe/Mg values of chlorite could still represent the composition of the former cordierite.

6. Stable Isotope Geochemistry

The oxygen isotope compositions of mineral separates were measured with the laser extraction

facility at the University of Lausanne (SHARP, 1990). Pure mineral separates were heated with a 20W CO_2 laser in the presence of a BrF_3 atmosphere. Samples were loaded in a high-purity nickel block; seventeen samples could be loaded simultaneously, of which three of four samples were standards. All data are reported relative to SMOW (Tab. 2).

The $\delta^{18}O$ values of the rhyolites are in the range of typical I-type granites (e.g., O'NEIL and CHAPPELL, 1977), but the other samples are all at the extreme ^{18}O -enriched range of I-type granites, and are more compatible with S-type granites (assuming the $\delta^{18}O$ value of the feldspars approximates the $\delta^{18}O$ values of the whole rock). The presence of muscovite, cordierite and andalusite as well as the corundum-normative CIPW norm and high aluminum content support the S-type characterization of these samples (e.g. TAYLOR, 1978). These granites can be categorized as either type I or type II high- ^{18}O magmas according to TAYLOR (1978). Both types I and II are assumed to have undergone extensive isotopic (and chemical) interaction with pelitic rocks. The difference between these two types of magmas is related to their depth of interaction. Type I magmas are thought to have assimilated pelitic country rocks at depth. In this way, magmas brought to higher levels before crystallization should have relatively uniform $\delta^{18}O$ values. Type II magmas, by definition, have assimilated the country rock at higher levels – generally the level of magma emplacement. Type II magmas may undergo dynamic interaction with the surrounding country rock during crystallization. As a result, it is possible to have isotopic zoning in the pluton or between intrusive and extrusive equivalents. The rhyolites analyzed in this study have a lower $\delta^{18}O$ value than the granites, supporting a type II origin. In this case, the extrusive rhyolites would have had less time than the slowly-cooled granites to interact with the surrounding country rock. A more detailed study of the spacial distribution of $\delta^{18}O$ values in the granite (i.e., $\delta^{18}O$ values vs distance from the magma chamber–host rock contact) is required to provide further constraints on the classification of the granites. It is clear, however, that the ^{18}O -enrichment cannot be due to a low-temperature hydrothermal alteration as is observed in some granites (type III of TAYLOR, 1978). In these granites, the $\delta^{18}O$ value of the feldspar is elevated while the $\delta^{18}O$ values of the quartz are in the range of normal granites (WENNER and TAYLOR, 1976). In the Vallorcine granite, the $\delta^{18}O$ values of the feldspar are lighter than those expected from equilibrium fractionation with quartz (Fig. 4).

Tab. 3 $\delta^{18}\text{O}$ values compared to SMOW and D values with calculated temperatures.

Sample	Qz	Kfs	Plg	Bit	$\Delta\text{Q-Kfs}$	T°C	$\Delta\text{Q-Plg}$	T°C _{An20}	T°C K-Bi-Qz	$\Delta\text{Q-Bi}$	T°C
1a	11.34	9.59	–	–	1.75	470	–	–	–	–	–
1b	12.38	10.13	–	6.91	2.25	380	–	–	750	5.47	600
4	12.71	–	–	–	–	–	–	–	–	–	280
119/1	11.82	9.10	10.2	5.91	2.70	320	1.60	580	750	5.91	560
122	11.49	8.35	–	–	3.14	280	–	–	–	–	310
154	11.39	–	–	4.78	–	–	–	–	–	6.60	510
187/A	12.78	10.51	10.17	7.19	2.27	380	2.60	400	730	5.60	590
210	10.81	8.95	8.67	7.64	1.86	445	2.14	470	1680	3.17	920

Isotopic equilibrium between coexisting phases can be visually assessed with an isotherm plot following the method of JAVOY et al. (1970). In this method, the temperature coefficient of fractionation a is plotted against the $\Delta(\text{Qtz} - \text{min}) - b$ where these two quantities are related by the equation

$$\Delta(\text{Qtz} - \text{min}) = a \cdot 10^6 / (T^2) + b \quad (1)$$

If all phases are in equilibrium they should define a straight line of a vs $\Delta(\text{Qtz} - \text{min}) - b$ where the slope is equal to $1/(T^2)$. The highest temperatures are preserved in the rhyolite, which approaches temperatures of 650 °C. All other samples have elevated $\delta^{18}\text{O}_{\text{feldspar}}$ values (except the anomalous plagioclase porphyry sample 119/1), indicative of minor high-temperature hydrothermal alteration or mineral/mineral, mineral/fluid isotopic retrograde exchange, and which could correspond to the local formation of late topaz or tourmaline.

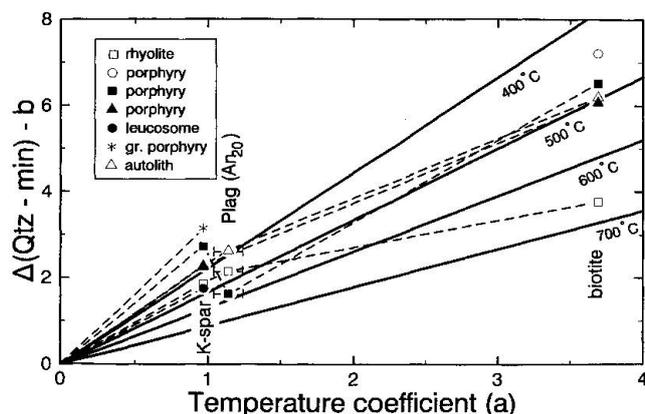


Fig. 4 Isotherm plot (JAVOY et al., 1971) for mineral separate data from the Vallorcine granite. The temperature coefficient a is related to $\Delta(\text{Qtz} - \text{min}) - b$ by equation 1. Temperature coefficient data are taken from JAVOY (1977) assuming an $X_{\text{anorthite}}$ component in plagioclase of 0.2. Shown are isotherms for 400 °C, 500 °C, 600 °C and 700 °C.

7. Whole rock chemistry

7.1. DATA

Seventy eight samples were analyzed for 30 major and minor elements (Fribourg University, Tab. 4), and eight of these samples were also analyzed for REE and U/Th (CRPG, Nancy, Tab. 5).

Projections of meso-normative minerals in the QAP-diagram (STRECKEISEN, 1976) of the porphyry type of the Vallorcine granite (colour index 10–30), the even grained, aplitic type (colour index 0–8), and the leucogranite (colour index 0–10) are classified as alkali feldspar-granites and granites; in the Or-An-Ab diagram, the leucogranites, granite-porphyrries and the bulk of the porphyritic granites are alkali feldspar-granites, and some of the porphyritic granites plot also in the field of (syeno)granite and granite. The grey rhyolitic rocks can be determined as rhyo-dacites or dacites.

Variation diagrams demonstrate (Fig. 5), that the major and trace elements exhibit a common chemical trend, namely a decrease of FeO, Al_2O_3 , TiO_2 , CaO, MgO, Zr, Y, $\text{Ree}_{(\text{tot})}$, and the increase of K_2O and Na_2O with rising SiO_2 -values. The trends follow a sequence from the autoliths, porphyritic granite (lower facies), porphyritic granite (higher facies) to granite-porphyrries. Among the rhyolites, two main types should be differentiated, grey rhyolites with mainly low SiO_2 values, and late, red rhyolites with high SiO_2 values. But for the latter more data are needed to allow a more precise discussion on their chemical patterns.

The REE (Fig. 6) display flat-lying distribution curves with abundances of 100 to 10 times chondrite, and slight negative europium anomalies, a pattern typical for biotite- and two-mica granites. The Eu-anomalies may be caused by slight oxidizing conditions at depth, thus enabling a preferred incorporation of Eu^{2+} instead of Ca^{2+} in the early crystallizing plagioclase (HENDERSON,

Tab. 4 Bulk rock composition of the analysed granites (% for oxides, ppm for traces).

	Porphyritic granites						Leuco-granite	Auto-lith	Granite Porhyry	Rhyolite
	D ¹⁾	D	H ²⁾	H	H	H				
	1b	4	22	34	74	168	1c1	4/1	122	1466 ³⁾
SiO ₂	68.29	69.39	74.75	74.32	72.97	73.95	75.77	69.06	74.18	72.89
TiO ₂	0.63	0.61	0.28	0.28	0.26	0.28	0.08	0.72	0.14	0.13
Al ₂ O ₃	15.21	15.22	13.65	13.55	14.29	14.61	14.49	15.6	14.7	14.43
Fe ₂ O ₃	3.99	3.92	1.71	1.56	1.45	1.83	0.36	4.47	1.24	0.76
FeO	2.93	2.61	1.1	1.08	0.86	1.12	0.41	3.18	0.63	0.53
MnO	0.06	0.05	0.03	0.02	0.05	0.05	0.02	0.06	0.05	0.02
MgO	1.16	1.28	0.52	0.47	0.42	0.53	0.15	0.39	0.32	0.17
CaO	1.79	1.28	0.52	0.5	1.58	0.51	0.54	1.74	0.55	0.56
Na ₂ O	3.35	3.02	3.22	4.51	3.3	3.69	3.87	3.12	4.33	3.45
K ₂ O	4.87	4.8	4.82	4.97	5.29	4.33	4.09	4.23	4.42	5.16
P ₂ O ₅	0.26	0.28	0.32	0.32	0.34	0.31	0.3	0.29	0.41	0.41
Total	99.61	99.85	99.86	100.5	100	100.1	100.81	100.68	100.25	99.77
H ₂ O ⁺	0.66	0.96	0.91	1	1.7	1.05	0.74	0.8	0.95	1.26
H ₂ O ⁻	0.19	0.03	0.02	0.06	0.04	0.1	0.03	0.02	0.01	n.d.
Nb	14	13	12	15	16	18	8	18	23	17
Zr	218	198	113	124	109	100	34	244	60	64
Y	25	27	8	15	14	11	3	33	7	9
Sr	171	167	83	84	76	60	26	157	34	47
Rb	226	229	236	262	293	289	225	234	399	404
Th	17	16	17	18	14	11	6	17	14	8
Pb	27	28	24	24	25	20	16	25	20	n.d.
Ga	22	22	19	19	18	22	24	23	24	21
Zn	68	59	36	36	40	33	27	67	46	42
Cu	17	11	11	9	9	11	11	8	10	12
Ni	50	57	62	43	63	82	87	68	35	5
V	47	58	17	16	14	17	8	55	7	5
Cr	34	39	31	25	27	35	30	44	16	106
Ba	771	662	383	413	376	258	94	544	130	307
Total	1707	1586	1052	1103	1092	969	596	1537	825	1047

Methods used: Major elements analysed on fused beads (sample: Li₂BO₃ = 1.5) and corrected for matrix effects, absorption etc. with fundamental alpha-factors (DE JONGH, 1979). Traces analysed on pressed powder according NISBET et al. (1979). FeO determined with colorimetric methods (WILSON, 1960). H₂O calculated from ignition loss. Analyst: G. Galetti (major, minor elements).

¹⁾ D: porphyritic granite of lower levels; ²⁾ H: porphyritic granite of upper levels.

³⁾ Analysts: Service des Analyses, CRPG (Nancy).

1984; CULLERS et al., 1980). The continuous decrease in REE observed throughout the whole suite may be the consequence of early crystallization of biotite and apatite extracting REE from the melt.

7.2. GEOCHEMICAL CHARACTERISTICS

Based on the trends mentioned above (Figs 5, 6), we conclude that the different granite types de-

fine a differentiation sequence with the leucogranites as the first melting product. The low Na₂O contents < 3.2 and the molar ratio of Al / (Na + K + 2 Ca) > 1.1 establish these granites as S-type granites (CHAPPELL and WHITE, 1974). This is confirmed when P₂O₅ and the molar ratios of Al / (Na + K + 2 Ca) (> 1.1) are compared. The concentrations of P₂O₅ do not follow the theoretical model (HARRISON and WATSON, 1984), but display a curved trend of P₂O₅ contents with rising SiO₂.

Tab. 5 Rare earth analyses of selected granite samples (see Fig. 6)

	La	Ce	Nd	Sm	Eu	Gd	Dy	Er	Yb	Lu	Y	Ree	La/Y	La/S	Gd/Y	Eu/Eu*
1b	38.5	83.7	53.3	7.1	1.2	5.96	4.82	2.41	2.16	0.28	30.9	129	10.5	3.39	2.06	0.56
1c 1	4.29	9.11	3.16	1.06	0.17	0.9	0.89	0.53	0.57	0.08	6.76	70.2	4.47	2.53	1.18	0.53
4	36.9	78.9	32.3	7.08	1.11	6.24	5	2.54	2.27	0.3	32.3	147	9.66	3.26	2.05	0.51
22	21.6	47.0	19.8	4.13	0.53	3.34	2.19	0.94	0.8	0.08	12.5	93.6	16.0	3.27	3.11	0.43
122	15.0	32.1	13.7	3.28	0.56	2.87	2.32	1.08	0.93	0.19	14.0	80.0	9.60	2.87	2.30	0.55
34	22.2	45.6	19.7	4.19	0.59	3.41	2.56	1.12	0.98	0.17	15.2	99.9	13.4	3.31	2.59	0.47
74	20.7	46.5	18.4	4.32	0.64	3.68	2.72	1.16	1	0.15	16.5	91.3	12.3	3.0	2.74	0.49
168	16.1	34.8	13.6	3.22	0.42	2.53	2.16	1.04	1.02	0.14	14.2	50.9	9.37	3.13	1.85	0.44
1466	33.2	16.0	13.8	3.13	0.31	2.53	2	0.94	0.81	0.41	13.4	86.3	19.8	5.13	3.12	0.10

Centre d'analyses du Centre de Recherches Pétrographiques et Géochimiques (Nancy) analysts; ICP analysis.

The relative high value of P_2O_5 (Fig. 7) correspond to the trends observed in peraluminous granites (BEA et al., 1992; PICHAVANT et al., 1992). The S-type character of the granites is confirmed by the $\delta^{18}O$ values (discussed in chapter VI). The very high, normative corundum-contents (Tab. 6) point to peraluminous granites (confirmed by the presence of the Al-rich phases muscovite, cordierite, andalusite, sillimanite). We thus conclude, that the granites are anatectic products of metapelites and metagreywackes, and such rocks are the main country rocks of the granite body, also at lower levels (P-t conditions corresponding to lower to middle crust), and comparable source rocks are confirmed by the plot in the R_1 - R_2 diagram (DE LA ROCHE et al., 1980; BATCHELOR and BOWDEN, 1985) (Fig. 8).

Despite the attempts to chemically define granitoids (PEARCE et al., 1984) no satisfactory scheme exists to discriminate granites from one specific plate-tectonic origin. Following PEARCE et al. (1984), this type of diagram is not suitable for granites produced by a continent-continent-collision or by rising mantle material. The Vallorcine granites plot in the syncollisional field (Fig. 9) after these authors which, obviously, is the characteristic pattern for many of the Late Variscan granitoids in the Alpine domain (BONIN et al., 1993). This could be the expression of a rather comparable process of granite formation over a wide area during the Late Variscan, but, more probably, it shows the limits of a classification, where many granitoids formed over a time of about forty millions years and plot into one area, although an evolution trend should be recognizable during such a long time span (BONIN, 1988). A strong differentiation is indicated in the Ba-Rb-Sr projection (Fig. 8), where the late granites show high Rb/Sr ratios. The accompanying rhyolitic rocks can be classified, after WINCHESTER

and FLOYD (1977), as dacites and rhyodacites with an evolution trend to rhyolites.

8. Genetic considerations

Considering the field observations and P-T data from country rocks (garnet-gneisses and amphibolites; JOYE, 1989), the Vallorcine granite intruded a high grade metasedimentary series, where strike-slip movement and formation of mylonites, at least, facilitated emplacement of melts. The mylonites passed the 500 °C geotherm at 300 Ma (Rb/Sr thin slab method, THÖNI in JOYE, 1989), and recent data on the anatexis linked to the regional dextral strike slip yielded a concordant age of about 317 ± 2 Ma (U/Pb on monazite, BUSSY and VON RAUMER, 1993) from the Lognan area (Mont-Blanc Massif) presently situated few kilometres to the south.

Zircon analysis, composition of biotites and rock chemistry of the granites plead for a heterogenous magmatic source comprising meta-greywackes, meta-pelites, granitoid gneisses and amphibolites. Element concentrations plead for secondary changes due to accumulative processes and assimilation. A first indication of temperature range of 800–900 °C is given by few feldspar-feldspar pairs (HASLTON et al., 1983; STORMER, 1975; BROWN and PARSONS, 1981). Indicators of pressures about 10 Kb and "dry" conditions result from granulite facies rocks in the Aiguilles Rouges massif (VON RAUMER et al., 1993). The granitoids might thus have their origin in the lower to middle crust (see below).

If plotted in the Qu-Ab-Or diagram (Fig. 10), the trend towards lower pressures displays a general shift of the points to higher Or values, this evolution being the image of early plagioclase followed by K-feldspar. Interpreting EBADI and

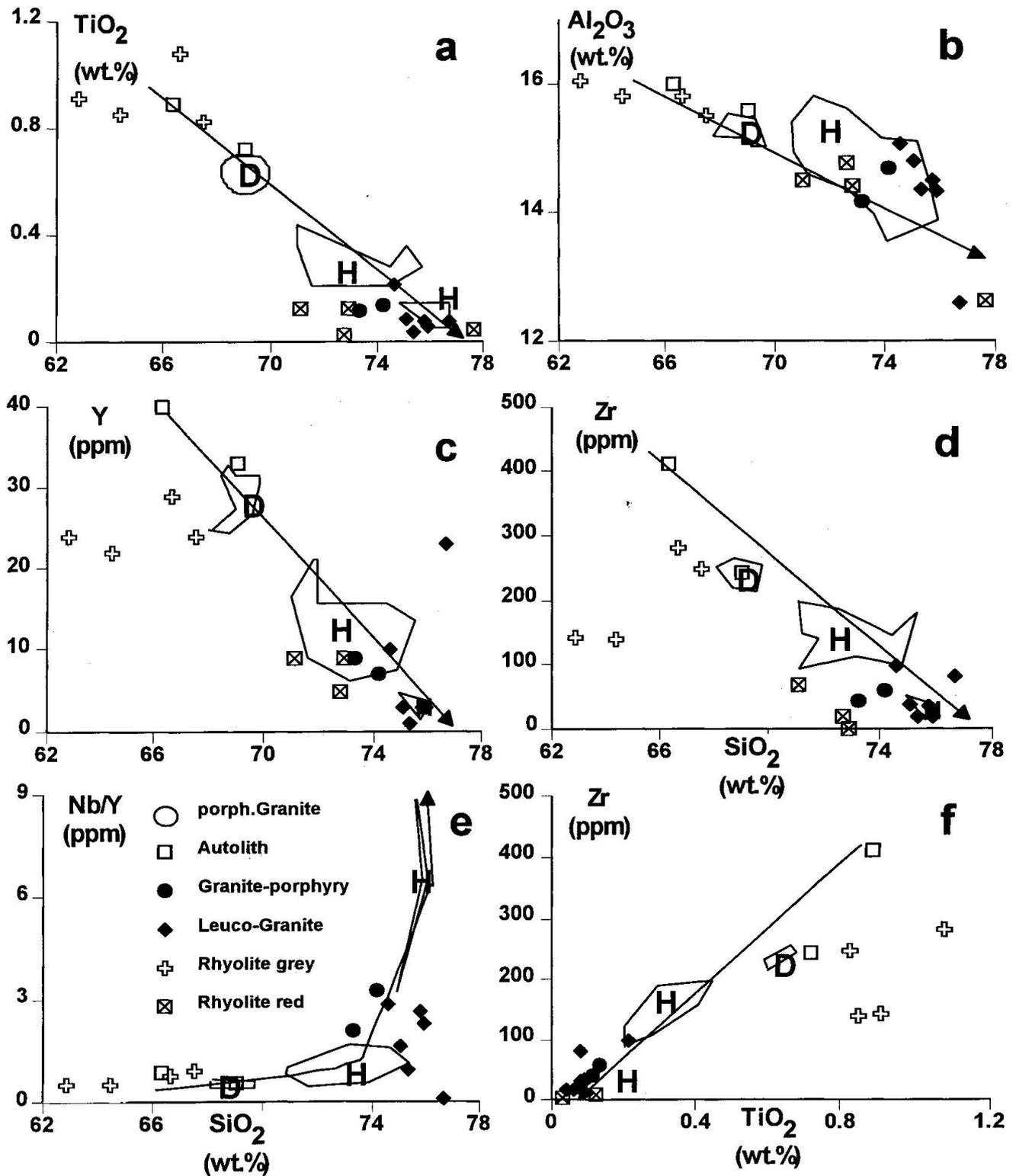


Fig. 5 Chemical variation of the Vallorcine granite types. a-e: TiO_2 , Al_2O_3 , Y, Zr, Nb/Y compared to SiO_2 . Trends indicate an evolutionary trend with increasing SiO_2 from grey rhyolites, autoliths to deep porphyric granites (D), high porphyric granites (H), the granit porphyry towards the highest values of the Leuco-granites and red rhyolites. f: Zr compared to TiO_2 , comparable patterns as in a-e, Zr decreases towards the highly evolved endmembers of the sequence. (Trace analyses on rhyolites were only made for some chosen samples.)

Tab. 6 Variation of chemical parameters of granites and rhyolites.

	Autolith	Granit-porphyr	Leucogranite	Porphyric granite	Rhyolite
Na ₂ O	3–3.1%	3.1–4.3%	2.1–4.1%	2.5–4.1%	2.3–4.2%
K ₂ O	4.13–4.23%	4.3–4.4%	2.6–5.4%	4.1–5.8%	3.0–5.8%
A/CNK	1.3	1.1–1.3	1.27–1.47	1.0–1.44	1.09–1.77
SiO ₂	66–69%	73–74%	74.5–76.5%	68.2–76%	62.8–77.6%
c	2.9–3.3	2.75–4.26	2.7–4.8	0.6–4.9	1–3
P ₂ O ₅	0.29–0.35	0.4	0.09–0.38	0.26–0.39	0.11–0.41

JOHANNES (1991), this shift indicates water activities below 1 during ascent of magma which may have reached rather shallow levels (± 1 Kb). The minimal water content of 0.6–1% (calculated from the ignition loss of fresh granites) could be attained by dehydration of 15–25% of hydrous

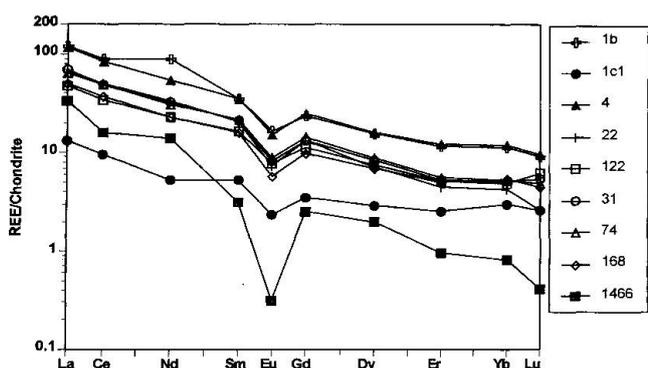


Fig. 6 REE distribution pattern for selected samples of the Vallorcine granite (chemistry and classification, see Tab. 2).

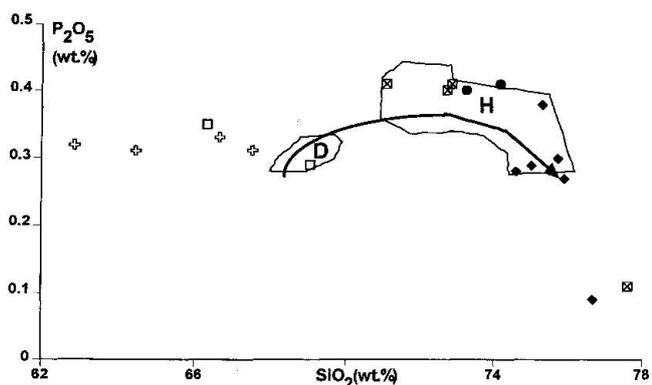


Fig. 7 Distribution pattern of P₂O₅ in the different granite type of the Vallorcine granite. The relative high phosphorous content of the Vallorcine granite is indicative for peraluminous granites (BEA et al., 1992; PICHAVANT et al., 1992). The curved trend might be due to cumulation processes, accompanied by and/or mixed with effects of restitic apatites in the melt.

minerals in the source rocks, and metapelites with 15–25% biotite are abundant in the Aiguilles Rouges massif. Taking the temperature / pressure framework of 800 °C / 10 Kb as the initial values would allow the formation of about 15–25% of initial melt (JOHANNES and HOLTZ, 1990). The further evolution of the melts depends on the pressure-temperature path. Taking into consideration that strike-slip triggered the emplacement of the granite body, ascent of magma might have occurred at rather constant temperatures during decompression which, after JOHANNES and HOLTZ (1990), could have considerably increased the quantity of melt. During decompression to 5 Kb and constant temperature (800–900 °C) activity of water would remain rather constant and quantity of melt would attain 20–60%, and at lower pressures even much more. Diapiric ascent is con-

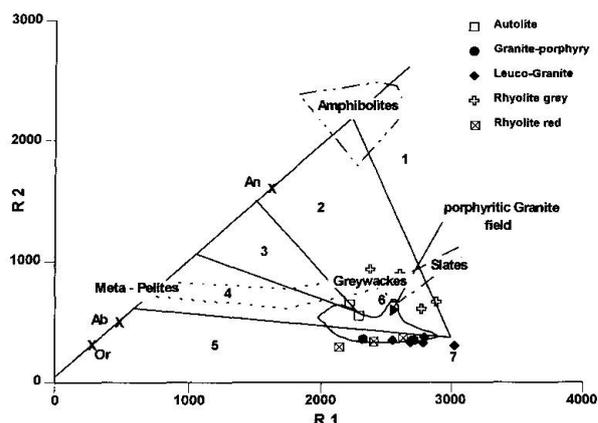


Fig. 8 R₁-R₂-diagram after DE LA ROCHE et al. (1980), BATCHELOR and BOWDEN (1985): R₂ = 4 Si - 11 (Na + K) - 2 (Fe + Ti), R₂ = 6 Ca + 2 Mg + Al; the sample points display the anatectic origin of the Vallorcine granite and the different source rock compositions (from BATCHELOR and BOWDEN, 1985): 1 = mantle differentiates, 2 = pre-collisional, calc-alkalic, 3 = post-collisional, calc-alkalic, 4 = late orogenic, subalkalic, 5 = anorogenic, alkalic, 6 = syncollisional, anatectic, 7 = post-orogenic, anatectic.

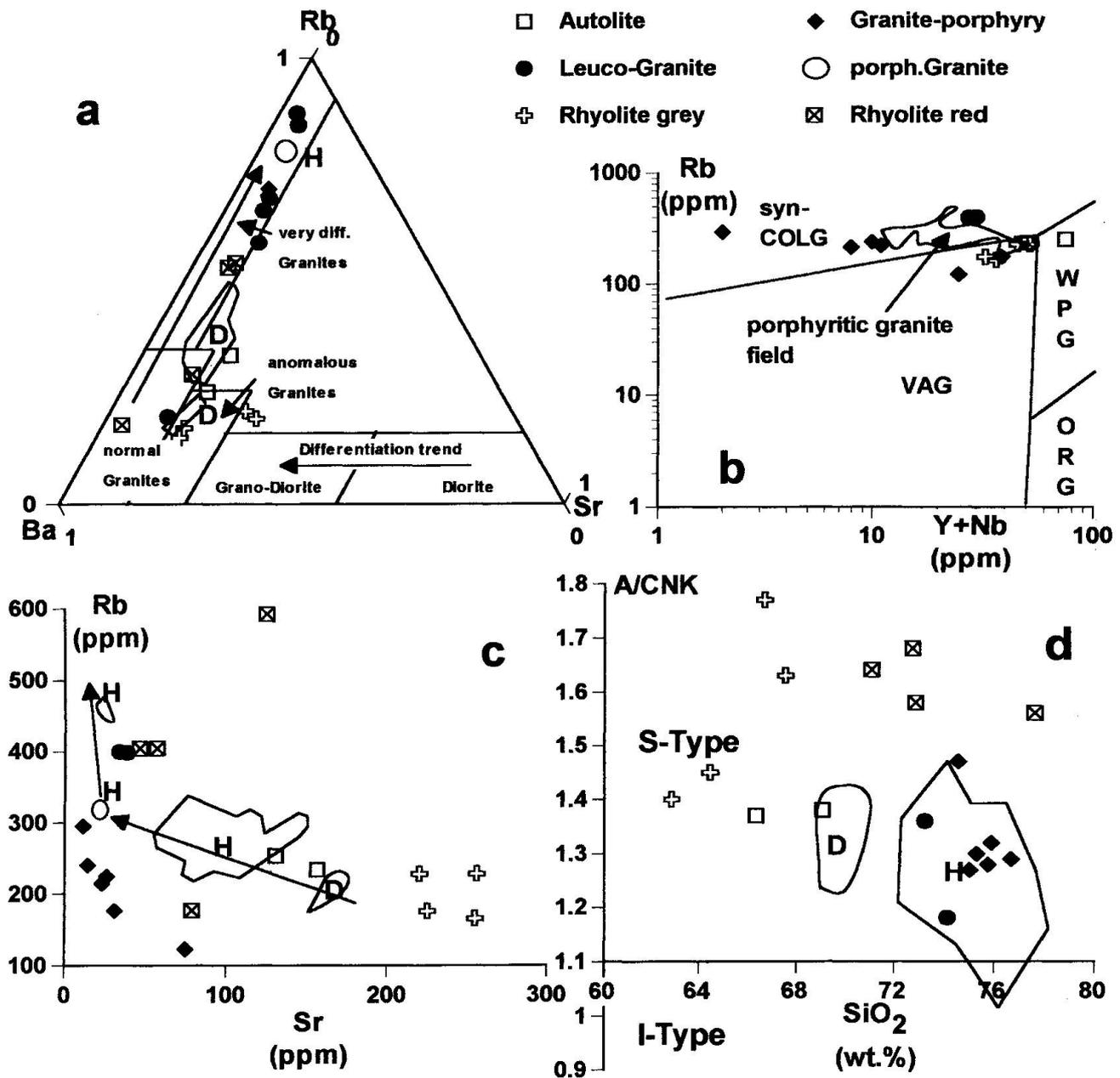


Fig. 9 Trace-element evolution of the Vallorcine granite types. a: Rb-Nb/Y diagram after PEARCE et al. (1984), showing the Vallorcine granite mainly as syncollisional; b: A/CNK diagram after CHAPPELL and WHITE (1974), all samples except one are S-type granites; c: Ba-Rb-Sr trends after EL BOUSEILY et al. (1975), reflecting a strong differentiation of the leuco-granites and the red rhyolites; d: Rb/Sr diagram indicating different trends for the leuco-granites and the main porphyritic granites, sequence as in figure 5.

firmed by a sometimes visible vertical orientation of large feldspar crystals and the sequence from more basic rocks at the bottom (e.g. Miéville) to the leucocratic types of the porphyritic granite at the top (more than 1000 m higher) with some aplitic veins of the pneumatolytic end stage.

Equilibrium between melt and plagioclase is attained, after JOHANNES (1989), at about 800 °C. Considering a source rock with plagioclase of about An₄₀₋₄₅ (syenitic orthogneiss or metapelite

with high An-plagioclase), a rather large quantity of melt should have formed, as there are almost no relict plagioclases left and the cores of the plagioclases are of An₃₀₋₄₀. In consequence, the rims of the plagioclases should have formed at rather constant temperatures during ascent of magma into shallower levels.

Pinitization of cordierite and chloritization of garnet (the latter contained in fresh biotite) might have occurred during an early ascent of magma

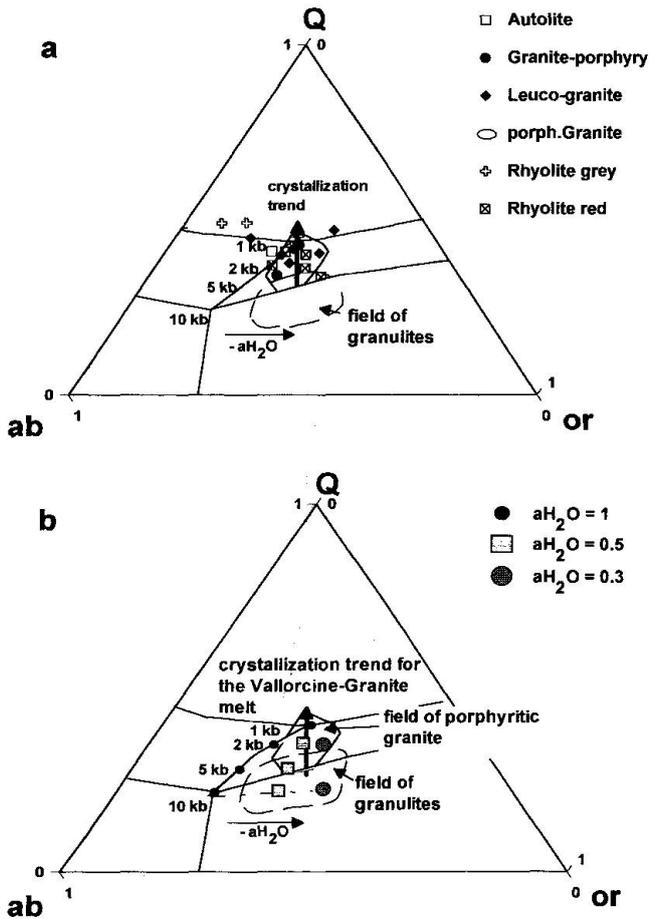


Fig. 10 Qu-ab-or projections after JOHANNES and HOLTZ (1990). *a*: evolution trend of Vallorcine granite from field of "granulites" (P,T, aH₂O) towards the eutectic point at 1 Kb or even lower pressures. *b*: Evolution trend of Vallorcine granite from low water activities towards aH₂O = 1, compared with data points for melt compositions at different aH₂O from HOLTZ and JOHANNES (1990).

into shallower (subvolcanic) crustal levels. After rather complete fusion of the crystal mush on its way through the upper crust, evolution of magma probably changed from decompression to cooling conditions accompanied by differentiation. The distribution of a low, coarse grained porphyritic granite, a middle level of less coarse grained porphyritic granite and the fine grained granites as well as the granite-porphyrines and aplites indicate fractional crystallization.

We thus conclude, that the process of fusion must have taken place under conditions of lower crust under low water activities, where water freed through dehydration melting was directly diluted in the melts. Such conditions correspond well to those indicated by the field of "granulites" (Fig. 10) considered by JOHANNES and HOLTZ (1990). The magmatic ascent occurred under rather isothermic conditions and was triggered by

decompression until higher crustal levels. Only at shallower levels this adiabatic evolution was followed, during the cooling stage, by an internal differentiation through fractional crystallization yielding the different types of granite visible today at surface. The granite solidus might have been lowered by Li, F, Be, as such elements are enriched in higher levels of the granite (but no precise data can be discussed). Such chemical variations might have moved the solidus curve in the stability field of andalusite (EINFALT, 1979; D'AMICO et al., 1981) which, in consequence, could form as a true magmatic mineral. During a late stage, disequilibrium of stable isotopes (feldspars) could indicate the establishment of a local hydrothermal convection system with transformation between 500–280 °C and leading to the formation of tourmaline and topaz. Considering limited transformation of the wall rocks, the convection system must have been quite restricted to the granite body and its cracks and faults.

According to VON RAUMER (1984 a, b), Alpine metamorphism attained only lower greenschist facies grade and had no influence on the mineralogy and chemistry of the rocks. K/Ar determinations on biotite and fission track analysis on zircons (SOOM, 1989) indicate, that temperatures never exceeded 220 °C.

9. Correlation with the Variscan framework

The Vallorcine granite is a rather small granite body which should not represent an exception and should not be separated, in its evolution, from that of the larger Variscan framework, where it certainly represents one moment in the very longlasting geologic evolution.

Comparable to the pieces of Variscan crust around the Alpine domain, also in the Variscan basement of the Alps a long period of granite formation since the Carboniferous (BONIN et al., 1993) and over wide areas is known (VON RAUMER and NEUBAUER, 1993). Most granites document different steps in a plate tectonic evolution (BONIN, 1988) during a rather late period of Variscan evolution. The Vallorcine granite, a syncollisional granite (PEARCE et al., 1984), and typical S-type granite, plots into the large field of Moldanubian S-type granites, when compared with the corresponding diagrams of FINGER and STEYRER (1990). In contrast, it plots into the overlapping region between I-type and S-type granites, when the K₂O/Na₂O values are compared.

In the surrounding domains outside the Alps, the late Variscan evolution indicates rather contrasting styles. Crustal convergence and a subse-

quent extension are documented from the southern Schwarzwald (ECHTLER and CHAUVET, 1992), Vosges (REY et al., 1992), and extensional tectonics with formation of collapse basins in a metamorphic core complex are discussed for the Montagne Noire (ECHTLER and MALAVIEILLE, 1990). Collapse of a thickened Variscan crust and the corresponding thermal history in the southern Massif Central were largely discussed by MALAVIEILLE et al. (1990) and MONTEL et al. (1992). The establishment of larger convection systems with hydrothermal - meteoric fluids is discussed by SIMON (1990), TAYLOR et al. (1991) and MAZUREK (1992) for the southern Schwarzwald and adjacent areas.

We necessarily have to place the Vallorcine granite in this pattern of evolution between crustal shortening and extension, a regional situation compared to that of the "basin-and-range-type" of Tertiary age (GRAF, 1992). The existence of large-scale strike-slip during this late period triggered the intrusion of the granite body, and trans-tensional conditions led to the formation and ascent of the magma, whereas following transpressional conditions led to the later overprint. The Vallorcine granite as a step in the granite evolution will be subjected to a comparative geochemical study with the different older and younger granites of this region.

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