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# Metasomatic Granitization of Ophiolites at the Southern Tip of the "Aiguilles-Rouges" Range (Western Alps)

By *Roger Laurent* (Quebec, Canada)\*)

With 5 figures and 2 tables in the text

## Abstract

During the Hercynian (Upper Carboniferous), a syntectonic metasomatic monzogranite was generated along an anticlinal hinge in mid-Paleozoic metamorphic "Greenstone Series" at Pormenaz in the Aiguilles-Rouges (External Crystalline Massifs of the French Alps).

Potash feldspar porphyroblasts (up to 8 cm long) were formed in metamorphic ophiolite (prasinite) by metasomatic addition of  $K_2O$  and  $SiO_2$  supplied by remobilization of subjacent granodioritic basement. The K-feldspar is different in each step between massive prasinite (plagioclase  $An_{30}$ -hornblende-pistacite  $\pm$  calcite-sphene-magnetite) and the resulting porphyritic low-silica (56%  $SiO_2$ ) "granite" (orthoclase-oligoclase-quartz-biotite  $\pm$  zircon-sphene-hornblende-calcite-magnetite), showing the evolution: augen perthitic microcline (banded and augen prasinite)  $\rightarrow$  triclinic orthoclase (orthogneiss)  $\rightarrow$  prismatic monoclinic orthoclase ("granite").

The granite evolved in five kinematic stages:

1. *Porphyroblastesis*, characterized by chemical mobility. The minerals (noted above) were formed in the crest of the embryonic anticline. During this phase, temperatures in the granite core probably exceeded 530° C, because K-feldspars attained monoclinic symmetry (orthoclase) and were formed in the stability field of the paragenesis hornblende-plagioclase ( $An_{30}$ ).

2. *Diapirism*, characterized by mechanical mobility. As the anticline developed, the increased volume and decreased density of the granitized mass caused it to grow upward into a mushroom-shaped diapir (length 4500 m, width 1500 m, height 1500 m) along the mechanically weak axial plane.

3. *Cataclasis*: Now having reached the rigid zone of rupture (within 5 km of the surface), the "granite" became mylonitized, hydrothermally altered, and disrupted by closely spaced normal faults.

4. *Recrystallization*: With rise in temperature (K/Ar data) quartz, albite, and myrmekite formed, and aplites, kersantites, and ore-vein deposits were emplaced under a cover of about 1000 m of continental Upper Westphalian sediments ("Hercynian Molasse").

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5. *Erosion*: The granite was unroofed and supplied Stephanian conglomeratic arkoses. According to geochronometric and stratigraphic data, the total duration of the process, from porphyroblastesis to the time of erosion, is estimated to be about 60 m. y.

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## INTRODUCTION

It has often been suggested that water-rich and alkali-rich fluids are mobile and can easily react with other minerals and thus transform very considerable masses of country rock into granites. To be documented, this process of granitization needs to occur in rocks of strikingly different initial chemistry and mineralogy; such examples remain rare. We propose to describe the formation of a potassic monzogranite in a series of metamorphic ophiolites of spilitic composition.

## GEOLOGIC SETTING

The metasomatic "granite" forms Mount Pormenaz at the southern extremity of the Aiguilles-Rouges range in the French Alps, about 10 km southwest of the Mont-Blanc massif (fig. 1). Aiguilles-Rouges and Mont-Blanc are situated at the edge of the alpine foreland; they represent rooted fragments of the infrastructure of the Alps which project through the younger (Triassic to Tertiary) terranes of the alpine cover.

A greenstone belt of probable Silurian to Middle Carboniferous age extends more than 200 km through the French Alps. At Pormenaz, at its northern

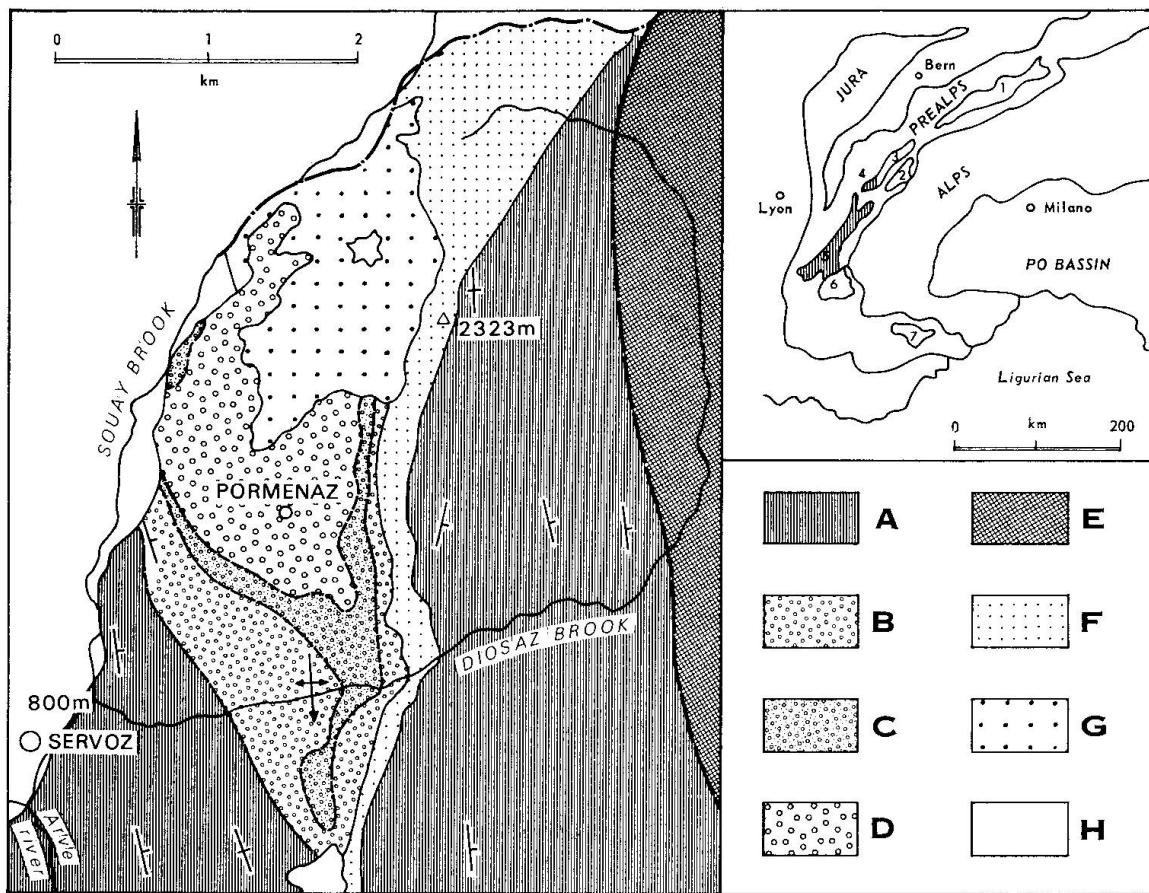


Fig. 1. Geographic and geologic setting of Mount Pormenaz (4) and the other External Crystalline Massifs of the Alps: Aar-Gothard (1), Mont-Blanc (2), Aiguilles-Rouges (3), Belledonne (5), Pelvoux (6), and Mercantour (7). Geologic map, simplified from R. LAURENT (1968): A, Greenstone belt (ophiolites); B, Marginal zone I of migmatitic facies; C, Intermediate zone II of agmatitic facies; D, Core zone III, potassic monzogranite; E, Old Gneiss Complex of the Aiguilles-Rouges; F, Upper Westphalian slates and sandstones; G, Stephanian conglomerates and arkoses; H, Triassic to Tertiary Alpine Sedimentary Cover.

end, it terminates against the older, possibly Precambrian gneiss complex of the core of the Aiguilles-Rouges. In the area of this contact, the greenstones were granitized during the Hercynian orogeny, about 350 m. y. ago.

The geology of the southern Aiguilles-Rouges has been recently described by LAURENT (1968). Detailed petrologic descriptions and chemical analyses of the greenstone belt have been given by C. BORDET (1961), DEN TEX (1949), LAURENT (1968), LE FORT and EHRSTRÖM (1969), and TOBI (1959).

#### STRUCTURES AND ROCK TYPES

The Pormenaz granite occupies the north-trending anticlinal hinge of the greenstone belt, and formed there in the lowest and most basic units of the



ophiolitic suite, into which it grades. The northern part of the stock is unconformably overlain by an arkosic conglomerate of Stephanian age (Upper Carboniferous) made up of debris and pebbles from the same granite (LAURENT, 1965). The problem of the genesis of the granite can be attacked by considering its shape and size, internal structures and variations of mineralogical and chemical composition, the nature of the environment during formation, and post-formation changes.

The granite forms a mushroom-shaped stock approximately 4500 m in length. It is 1500 m wide at its widest point, the roof of the diapir (top of Mount Pormenaz); 1000 meters below, where a good cross-section is provided by the Diosaz Brook, at the foot of Mount Pormenaz, its width is merely 150 m. It is therefore probably safe to assume that this granite disappears rapidly and completely at greater depth.

### 1. The Country Rock

The country rock is an ophiolite forming the base of a thick pile of metamorphosed volcanic and sedimentary rocks. The upper 6000 m of the pile consist of mica schists and very fine grained two-micas plagioclase gneisses. The lower 3000 m consist of metamorphosed basic, intermediate and acid volcanics, locally associated with well-preserved gabbros and peridotites.

The term *ophiolite* refers here to a metamorphosed igneous rock (extrusive or intrusive) containing as essential components sodic plagioclases, amphiboles (hornblende, actinolite), epidotes (pistacite, clinozoisite), and chlorite (clinochlore). Minor or accessory components include various amounts of quartz, calcite, sericite, magnetite, sphene, rutile, and leucoxene. The texture is heterogranular granolepidoblastic. The term *prasinitic gneiss*, a variety of ophiolite, applies to a relatively massive rock of the almandine-amphibolite facies characterized by a fine "augen" structure; the abundant augen consist of plagioclases a few millimeters long and are set in a finer green groundmass of epidotes, amphiboles and chlorites. A *prasinite* is the greenschist facies equivalent of the prasinitic gneiss; *ovardites* are chlorite-plagioclase ophiolites (without epidotes and amphiboles) associated with prasinites.

As indicated by their chemical composition (analysis 1, table I), the ophiolites derive from a sodic-gabbroidal magma; they have the typical chemical features of spilites which are, compared to average continental and oceanic basalts, richer in  $\text{Na}_2\text{O}$ ,  $\text{MgO}$ ,  $\text{H}_2\text{O}$ , and  $\text{CO}_2$ , but poorer in  $\text{K}_2\text{O}$ ,  $\text{CaO}$ ,  $\text{FeO}$ ,  $\text{Fe}_2\text{O}_3$  and  $\text{TiO}_2$ . The ratio  $\text{Na}_2\text{O}/\text{K}_2\text{O} \gg 1$  (fig. 2), and the Rittmann's series index  $\sigma = [\text{Na}_2\text{O} + \text{K}_2\text{O}]^2/\text{SiO}_2 - 43$  ( $\sigma = 5.30$  for the prasinitic gneiss, analysis 1) show that these spilites have moderate consanguinous affinities with basalts of the oceanic alkaline series (Atlantic).

The sodic character of the ophiolites remains constant, although the silica

content varies (analyses 1, 2, 3, table I). The bulk chemical composition changes from ultrabasic and basic at the bottom to intermediate and acidic in the upper units, where the ophiolites are frequently associated with keratophyric and rhyolitic members.

Through magmatic and metamorphic differentiation, the spilite-keratophyre sequence is actually fractionated into various monomineralic and poly-mineralic phases: amphibolites, epidotites, chloritites, albitites, carbonatites, ovardites, prasinites, and prasinitic gneisses. Those conditions suggest that no single analysis of a particular rock can give a true image of the primary composition of the magma (AMSTUTZ, 1968), but they are strongly indicative of the occurrence of large-scale chemical diffusion across the series. The presence of many monomineralic layers among the ophiolites is indeed evidence that severe restriction on the number of phases in individual layers has often been fulfilled and, consequently, that thermodynamic equilibrium was sought

Table I. *Chemical and Normative Composition of Spilitic Ophiolites*

Oxides (Wt. %)	1	2	3
SiO <sub>2</sub>	48.81	58.20	63.22
Al <sub>2</sub> O <sub>3</sub>	17.03	16.16	15.68
Fe <sub>2</sub> O <sub>3</sub>	1.65	2.54	1.50
FeO	5.93	3.10	3.73
MgO	7.28	5.40	2.52
MnO	0.15	0.09	0.06
CaO	7.32	4.47	1.54
Na <sub>2</sub> O	5.21	5.57	6.34
K <sub>2</sub> O	0.34	0.72	1.02
TiO <sub>2</sub>	0.88	0.54	1.45
P <sub>2</sub> O <sub>5</sub>	0.08	0.08	0.20
H <sub>2</sub> O <sup>+</sup>	2.77	2.36	2.51
H <sub>2</sub> O <sup>-</sup>	0.06	tr	0.06
CO <sub>2</sub>	2.92	—	—
	100.43	99.23	99.83
<i>Cation Norm</i>			
Quartz	—	5.12	13.61
Orthoclase	2.64	3.90	6.20
Plagioclase (Ab <sub>73</sub> An <sub>27</sub> )	63.45	(Ab <sub>74</sub> An <sub>26</sub> ) 68.05	(Ab <sub>90</sub> An <sub>10</sub> ) 64.35
Clinopyroxene	—	(Di <sub>100</sub> Hed <sub>0</sub> ) 3.68	—
Orthopyroxene (En <sub>75</sub> Fs <sub>25</sub> )	5.84	(En <sub>86</sub> Fs <sub>14</sub> ) 15.70	(En <sub>72</sub> Fs <sub>28</sub> ) 9.84
Olivine (Fo <sub>75</sub> Fs <sub>25</sub> )	15.69	—	—
Magnetite	1.81	2.68	1.51
Ilmenite	1.20	0.66	2.14
Apatite	0.13	0.13	0.30
Calcite	7.26	—	—
Corundum	1.93	—	1.99
	99.95	99.92	99.94

Analysis 1: Prasinitic gneiss (undifferentiated?), base of the Series

Analysis 2: Prasinite (spilite), differentiated member of the Series

Analysis 3: Ovardite (spilite), differentiated member of the Series

Cation norm calculated according to the method described by  
D. M. SHAW (1969)

and sometimes attained. This trend in the country rock indicates free chemical mobility during the processes of magmatic and metamorphic differentiation, resulting ideally in a gross chemical layering based on density stratification.

## 2. The Metasomatic Granite

The region of metasomatic granitization in the ophiolitic country rock can be divided into three zones (fig. 1) based on their respective structures, mineralogy and chemical composition.

### *Zone I (Marginal zone)*

The marginal zone of the metasomatic granite is 100 to 1000 m thick and is characterized by a migmatitic facies. In the fine grained ophiolites, banded and augen structures progressively developed through porphyroblastesis of microcline and low-albite microcline perthite accompanied by biotite and quartz. Because of strong enrichment in  $K_2O$  (analyses 4 and 5, table II), this zone corresponds chemically to a sharp inversion of the alkali ratio ( $Na_2O/K_2O$ ) that becomes smaller than 1 (fig. 2).

### *Zone II (Intermediate zone)*

A zone of agmatitic facies, varying from place to place in thickness (from a few meters to a maximum of 500 m) and composition, separates the marginal zone from the granitic core. In this heterogeneous zone the migmatitic ophio-

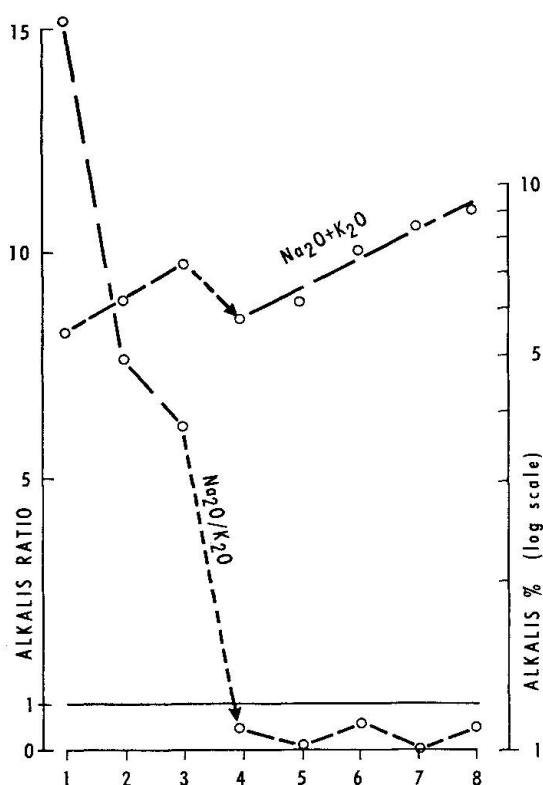


Fig. 2. Variation diagram of alkalis ratios and percentages for the spilitic (1, 2, 3; chemical analyses, table I), and metasomatized ophiolites (4, 5, 6, 7, 8; chemical analyses, table II).

lites, similar in composition to those of the marginal zone, appear to be invaded by and wrapped in a matrix of alkaline granite (analyses 6 and 7, table II). Pseudoidiomorphic orthoclases of widely varying triclincity and zircons constitute new important mineral phases in the matrix of the intermediate zone. In respect to the average composition of zone I, zone II is richer in alkalis and silica; as in zone I,  $K_2O$  exceeds  $Na_2O$  but the  $Na_2O/K_2O$  ratio seems to be highly variable: 0.66 in analysis 6, and 0.03 in analysis 7 (fig. 2).

### *Zone III (Core)*

The core of the metasomatic zone is homogeneous both in structure and composition and is 150 to 1500 m thick. Most of the rock (65–95 volume percent) consists of saussuritized oligoclase, biotite-chlorite, quartz, hornblende, sphene, zircon, calcite and magnetite. In this green groundmass, prismatic porphyroblasts up to 8 cm long of pink orthoclase (5–35 volume percent) give the granite a characteristic porphyritic structure. Many of the orthoclases are plagioclase-orthoclase perthites, which formed later during the phase of cataclasis. The orthoclases are prismatic and poikiloblastic; they are idiomorphic with a xenoblastic rim and contain, particularly in the rim region numerous inclusions of oligoclase ( $An_{30}$ ), biotite, epidote, sphene, apatite and quartz (fig. 3). By recrystallization, hornblende, as well as some of the sphene and quartz grew and engulfed minerals of the groundmass. Quartz is then green

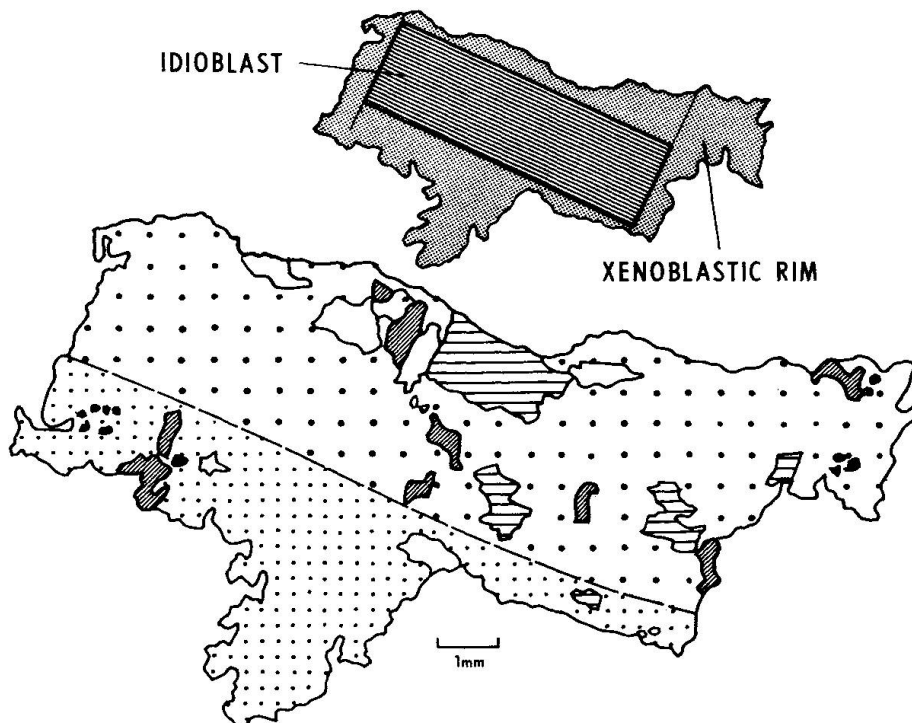


Fig. 3. Carlsbad twin of poikiloblastic orthoclase with idiomorphic core and xenoblastic rim. The potassium-feldspar is rich in mineral inclusions of plagioclase (widely hatched), biotite-chlorite (bold outline and hatched), quartz (blank), and magnetite (black).

because it contains abundant inclusions of chlorite and epidote. All the inclusions of the poikiloblastic minerals, as well as the groundmass of the rock, evidently represent relicts of the mineral phases of the pre-granitized ophiolite.

The final product of the granitization of the ophiolites has the chemical composition of a potassic monzogranitic magma (analysis 8, table II), intermediate between truly granitic and prasinitic. It is poor in  $\text{SiO}_2$  (56%), but rich in  $\text{K}_2\text{O}$  (5.81%) and contains a fair amount of  $\text{Na}_2\text{O}$  (3.10%).

Table II. *Chemical and Normative Composition of Granitized Ophiolites*

Oxides (Wt. %)	4	5	6	7	8
$\text{SiO}_2$	65.85	51.43	71.45	67.88	56.12
$\text{Al}_2\text{O}_3$	16.37	18.54	13.40	14.91	17.85
$\text{Fe}_2\text{O}_3$	1.36	4.26	0.49	2.99	3.29
$\text{FeO}$	3.76	6.57	2.18	1.27	2.03
$\text{MgO}$	1.80	6.33	1.53	0.98	3.56
$\text{MnO}$	0.02	0.01	0.02	tr	0.08
$\text{CaO}$	0.25	0.89	1.64	0.82	3.24
$\text{Na}_2\text{O}$	1.97	0.82	3.08	0.24	3.10
$\text{K}_2\text{O}$	3.89	5.37	4.64	8.20	5.81
$\text{TiO}_2$	0.86	0.67	0.60	0.99	1.14
$\text{P}_2\text{O}_5$	0.14	0.32	0.12	0.46	0.62
$\text{H}_2\text{O}^+$	3.06	4.66	1.32	1.74	2.43
$\text{H}_2\text{O}^-$	0.13	0.22	0.05	0.21	0.60
	99.46	100.09	100.52	100.69	99.87
<i>Cation Norm</i>					
Quartz	33.86	12.04	27.71	32.68	4.90
Orthoclase	24.10	33.70	28.05	50.60	35.40
Plagioclase	( $\text{Ab}_{97}\text{An}_3$ ) 19.30	( $\text{Ab}_{74}\text{An}_{26}$ ) 10.35	( $\text{Ab}_{79}\text{An}_{21}$ ) 35.30	( $\text{Ab}_{68}\text{An}_{32}$ ) 2.50	( $\text{Ab}_{76}\text{An}_{24}$ ) 41.05
Orthopyrox.	( $\text{En}_{55}\text{Fs}_{45}$ ) 9.60	( $\text{En}_{72}\text{Fs}_{28}$ ) 25.50	( $\text{En}_{62}\text{Fs}_{38}$ ) 6.44	( $\text{En}_{100}\text{Fs}_0$ ) 2.90	( $\text{En}_{100}\text{Fs}_0$ ) 10.26
Magnetite	1.33	4.78	0.51	0.87	2.40
Hematite	—	—	—	1.63	0.80
Ilmenite	1.28	1.06	0.90	1.50	1.60
Apatite	0.30	0.63	0.30	1.05	1.20
Corundum	10.18	12.08	0.74	6.21	2.33
	99.95	99.94	99.95	99.94	99.94

Analysis 4: Granitized ovoidite of marginal zone I

Analysis 5: Granitized prasinite of marginal zone I

Analysis 6: Alkaline granitic matrix of intermediate zone II

Analysis 7: Alkaline granitic matrix of intermediate zone II

Analysis 8: Leucomonzonite of core zone III ("metasomatic granite")

#### CHEMICAL TRENDS DURING METASOMATISM

In fig. 4A, major oxides have been plotted versus silica.  $\text{Na}_2\text{O}$  and  $\text{K}_2\text{O}$  are negatively correlated;  $\text{CaO}$  and  $\text{FeO} + \text{Fe}_2\text{O}_3$  also are negatively correlated although to a lesser degree. This seems to rule out the likelihood of a common magmatic source for the various members of that suite. They obviously do not show any simple pattern of magmatic differentiation.

With the help of fig. 4B, we may examine the particular behavior of major

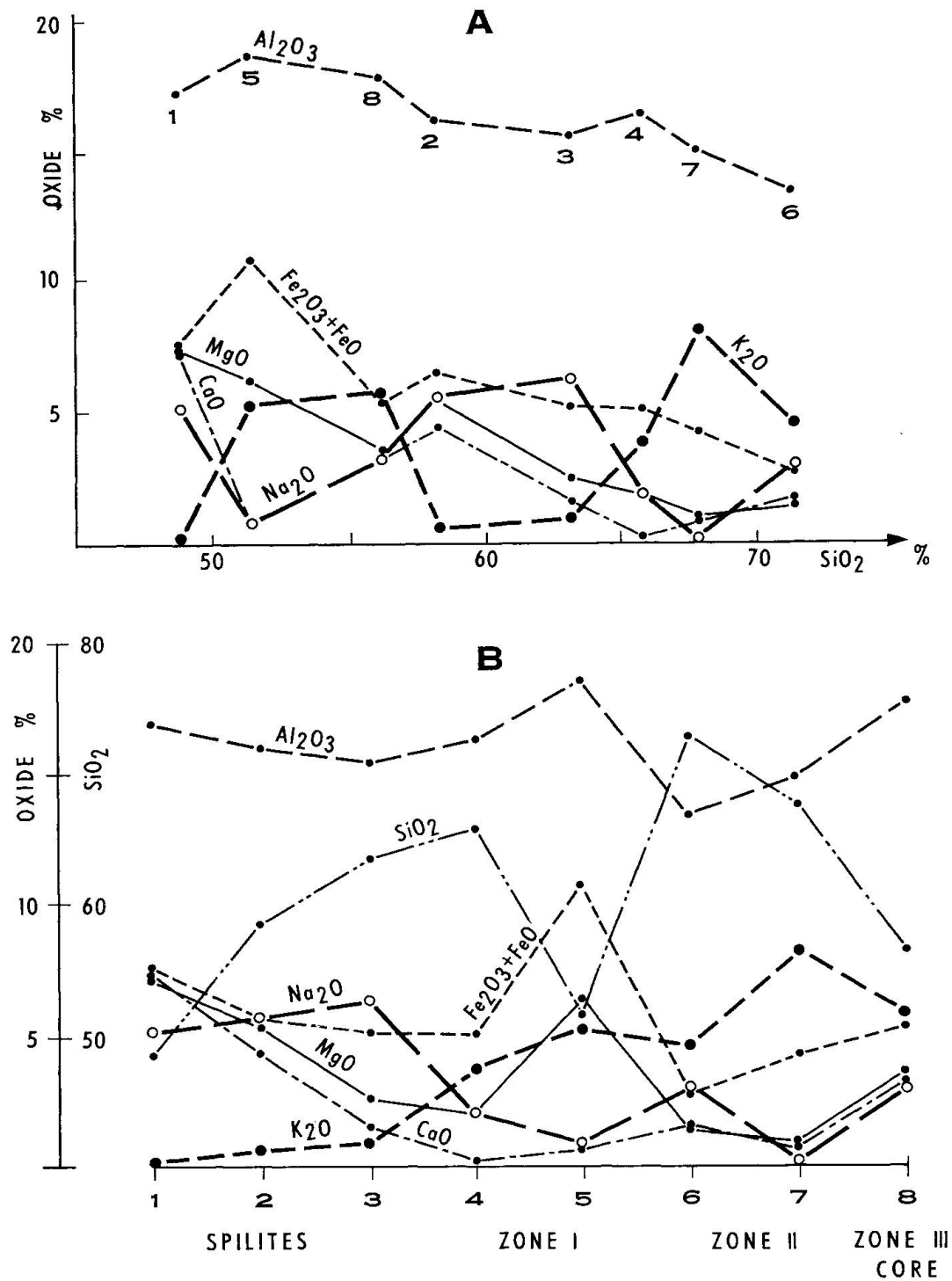


Fig. 4. Major element variation diagrams for the spilitic (1, 2, 3; chemical analyses, table I) and metasomatized ophiolites (4, 5, 6, 7, 8; chemical analyses, table II).

A Samples arranged according to their SiO<sub>2</sub> content.

B Samples arranged at an arbitrary distance according to their position from margin to core of the granitized zone.

oxides in the different zones of granitization. In the spilitic ophiolites (1, 2, 3), the chemical trend follows nicely a pattern of magmatic differentiation: the alkalis increase with silica, while the mafic elements (Ca, Fe, Mg) progressively decrease. The pattern however is strongly disturbed in zones I and II (4, 5, 6, 7) of granitization.  $\text{Al}_2\text{O}_3$ ,  $\text{FeO} + \text{Fe}_2\text{O}_3$ , and  $\text{MgO}$  tend to be somewhat enriched in the marginal zone I, relative to both intermediate and core zones II and III. At the same time  $\text{SiO}_2$  and  $\text{K}_2\text{O}$  tend to be enriched in the matrix material of the heterogeneous intermediate zone II, relative to both marginal and core zones I and III. This may be interpreted as the indication of outward migration of the mafic elements expelled from the zone undergoing stronger metasomatic granitization. On the other hand, zones I and II, structurally and chemically heterogeneous, represent more primitive and lower temperature stages of the granitization; their evolution stopped before homogenization was completed.

In the core, homogenization was completed. If we assume a metasomatic origin for the granite we can establish a chemical balance-sheet of the process, by comparing the composition of the original ophiolite (prasinitic gneiss 1) with the end product of granite (potassic monzonite 8). The granite is richer in  $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$ ,  $\text{K}_2\text{O}$ ,  $\text{TiO}_2$  and  $\text{P}_2\text{O}_5$  than the prasinitic gneiss, and poorer in  $\text{FeO} + \text{Fe}_2\text{O}_3$ ,  $\text{MgO}$ ,  $\text{CaO}$ ,  $\text{Na}_2\text{O}$  and  $\text{H}_2\text{O}^+$  (fig. 5). Particularly significant is the moderate increase in  $\text{SiO}_2$  and strong increase in  $\text{K}_2\text{O}$  assumed to have been supplied by silica- and potash-rich fluids from a source external to the ophiolites.

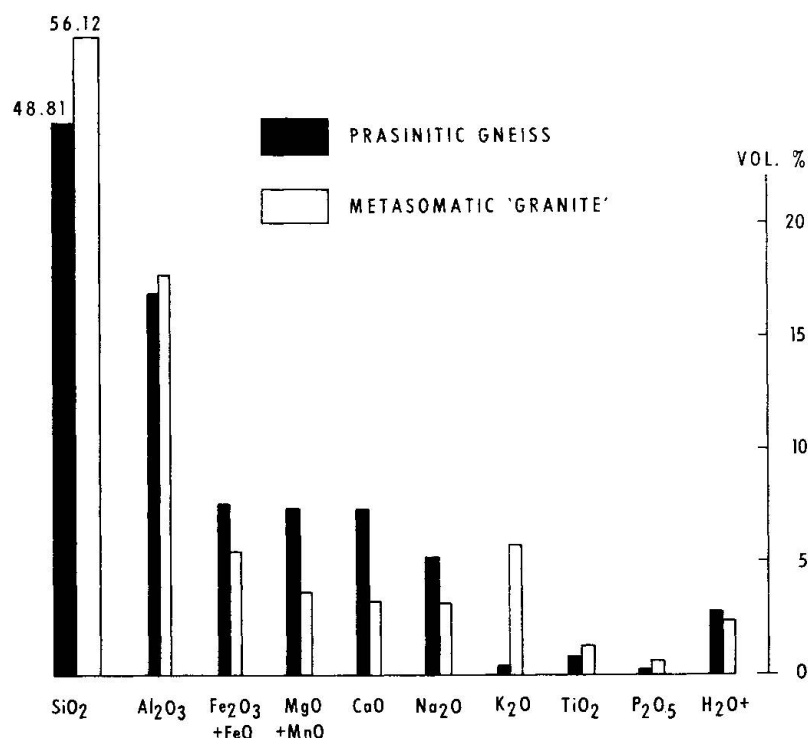


Fig. 5. Histogram: comparison between the chemical composition of the primitive country rock (spilitic ophiolite) and the final product of metasomatism (potassic monzogranite).

# PARAGENESIS: FACTORS AND ENVIRONMENTAL CONDITIONS OF METASOMATISM

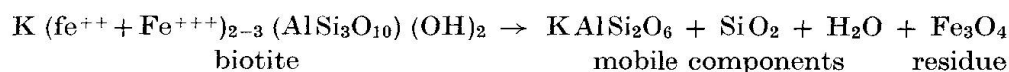
Chemical data indicate that granitization of the ophiolites of Mount Pormenaz corresponds to  $K_2O$ - $SiO_2$  metasomatism. Alkalis and silica are mobile components; they are easily soluble in hydrothermal solutions which can migrate in the form of an intergranular phase over long distances, and can eventually accumulate in a favourable structure, for example the hinge of an anticline. This requires a particular set of conditions: source of  $K_2O$ ,  $SiO_2$  and  $H_2O$ , favourable structure, favourable country rock, and a certain P-T environment. Those conditions seem to have been satisfied at Pormenaz.

## 1. Source

$K_2O$ ,  $SiO_2$  and  $H_2O$  are concentrated in the "residual system" of Bowen's model of magmatic fractional crystallization. The alkali- and silica-rich hydrothermal solutions could have been derived from the Mont-Blanc granitic batholith (fig. 1) that was emplaced contemporaneously with this metasomatic granitization. An alternative source for the solutions is the subjacent granodioritic basement. Experiments on remelting of rocks under high  $P_{H_2O}$  (e. g., VON PLATEN, 1965) showed that the first minerals to melt or redissolve are feldspars and quartz, the process yielding a potassium-rich anatectic melt. K/Ar age datings of biotites, feldspars and amphiboles in gneisses of the "Old Gneiss Complex" of the Aiguilles-Rouges (KRUMMENACHER and EVERNDEN, 1960; LAURENT, 1968) fall in the range 300 to 200 m. y., indicating that those Precambrian or Lower Paleozoic rocks have been reheated and probably remobilized during the Hercynian evolution.

It is significant that the metasomatic granitization occurs precisely at the contact between the ophiolitic series and the granodioritic core of the "Old Gneiss Complex". We therefore favour the second alternative, that  $K_2O$  and  $SiO_2$  were supplied by remobilization of the subjacent granodioritic basement. Of course, it is possible and even probable that this remobilization was triggered by heat from the Mont-Blanc batholith.

Some of the water for the metasomatism probably came from the ophiolites of spilitic composition that were and still are  $H_2O$ -rich, and possibly also from hydrothermal activity associated with the final stages of solidification of the Mont-Blanc granite. A third source of water may well have been the remobilized granodioritic basement, rich in hydroxyl minerals (biotite, hornblende). Water would have been provided along with  $K_2O$  and  $SiO_2$  through a reaction of the type:





## 2. Favourable Structure

The porphyroblastic feldspars formed in the crest of an embryonic anticline, which likely functioned as a trap for the granitizing solutions.

## 3. Favourable Country Rock

The effectiveness of metasomatic processes is based on the penetrability and reactivity of the country rock (MEHNERT, 1968). High porosity, flow and rupturing deformation will tend to facilitate the propagation of a fluid pore phase. Reaction between the paleosomatic mineral components of the country rock and the neosomatic fluid phase is also much more efficient where a large chemical contrast exists.

## 4. Pressure-Temperature Environment

The granitization is the second of four metamorphic events, each of which developed in a distinct pressure-temperature environment, as recorded in the several mineral assemblages.

In the first event, the country rock was metamorphosed in the almandine-amphibolite facies at the base of a volcano-sedimentary pile 9000 m thick. The rapid passage upward from amphibolite to greenschist facies, the absence of high-pressure minerals, and the relatively moderate thickness of the formation suggest a high geothermal gradient. The P-T stability fields and the water content of the various mineral assemblages of the ophiolites indicate for the maxima, a temperature of around 600° C and a water pressure between 3 and 4 kilobars. Thus, the geothermal gradient has been estimated to be of the order of 50° C/km and the depth of formation (base of the series) to be around 12 km (LAURENT, 1968).

In a distinctly later event, the ophiolites were granitized. The granitization was accomplished by  $K_2O-SiO_2$  metasomatism, which caused the formation of potassium feldspars in zones I, II and III. Judging from the migmatitic structures of zone I, metasomatism occurred during plastic deformation. Therefore, nucleation and growth of the porphyroblasts of potassium feldspar were probably accelerated and controlled by the kinematics of the deformation.

P-T conditions prevailing during metasomatism are reflected in the various types of potassium feldspars. X-ray diffraction studies using the separation of the (131) and ( $\bar{1}\bar{3}1$ ) reflections showed that the triclinicity of potassium-feldspars decreases progressively from zone I to zone III. Only microcline is present in zone I; in zone II "orthoclases" of varying triclinicity occur with microcline; in the core zone III, true monoclinic orthoclases have formed in coexistence with "orthoclases" of varying triclinicity and microcline. There-

fore, metasomatic crystallization produced feldspars with varying degrees of disorder of the Al/Si distribution. The partly ordered monoclinic orthoclase is stable through a large range of P-T conditions and forms at higher temperature than the fully ordered triclinic microcline, which is stable only below 500° C. A temperature of 500°–530° C for the transition triclinic-monoclinic is generally accepted on the basis of the work of GOLDSMITH and LAVES (1954). This suggests that the core of the granitized zone reached a temperature above 530° C during the formation of the orthoclases while the marginal zones always remained at a temperature lower than 500° C. Furthermore, the orthoclases of the core were formed in the stability field of the paragenesis hornblende-plagioclase  $An_{30}$ , which also indicates that the temperatures there probably exceeded 500° C.

The experiments of TUTTLE and BOWEN (1958) in the system  $NaAlSi_3O_8$ – $KAlSi_3O_8$ – $SiO_2$ – $H_2O$  showed that with increasing water vapour pressure the minimum temperature of the liquidus decreases progressively and at 4000 kg/cm<sup>2</sup>  $P_{H_2O}$ , is about 650° C. Therefore, feldspar assemblages can crystallize at relatively low temperatures under magmatic conditions if sufficient water is present. In the case of the Pormenaz granite, the core is structurally homogeneous and the porphyroblastic orthoclases are idiomorphic as if grown from a melt. The medium however was not entirely liquid because minerals of the pre-granitized ophiolite have been preserved in the groundmass and as solid inclusions in the orthoclases. The somewhat contradictory textural features of the granite suggest therefore a system characterized by both liquid and solid phases, leading to the development of a facies partly plutonic and partly metamorphic in character.

#### POST-FORMATION HISTORY

Two new metamorphic events characterize the post-formation history of the granite. During its ascent toward the surface, the granite and its country rock underwent cataclasis and alteration followed by partial recrystallization. Cataclasis produced homo- and heteromylonites in the roof of the diapir. The episode was accompanied by intense hydrothermal alteration and closely spaced cross faulting. The hydrothermal alteration was characterized by sericitization of alkali feldspars, saussuritization of plagioclases, and chloritization of mafic minerals. Coarse perthites formed deeper in the core, in response to stress and hydrothermal alteration.

This was followed by recrystallization which formed a mineral assemblage of the greenschist facies: quartz, chlorite, epidote and calcite, all of which cement the microfractures and joints, and muscovite, myrmekite and a generation of fresh albite, which tend to replace the crushed and pulverized feldspars.

Kersantites, aplites, quartz and barite with minor Cu-Pb-Zn vein deposits were finally emplaced along some of the open cross faults in the granite and its country rock. Shortly after this episode, the granite was unroofed and supplied Stephanian conglomeratic arkoses.

## CONCLUSIONS

### 1. Origin

The Pormenaz granite could theoretically be a product of any of three different processes: magmatic differentiation, granitic intrusion, or metasomatism. Magmatic differentiation can be ruled out because the country rock is essentially a sodic spilite, and, to my knowledge, the 200 km belt exhibits no indication of the presence of other potassic differentiates in the basal units of this "Greenstone Series". Structural and textural evidence also show clearly that granitization post-dates not only the primary magmatic crystallization of the ophiolites but also their primitive metamorphism.

The metasomatic effects of a granitic intrusion could produce the structural, textural, and chemical features of zones II and I. In this case, the peculiar chemical composition of the intrusion could reflect a large scale exchange of components with the country rock. However, an igneous intrusive origin is not reasonable in view of the disproportion between the small core and the large aureole. Furthermore, features within the core are not those of an intrusive rock.

In the core zone, chemical and textural features indicate a process of  $K_2O-SiO_2$  metasomatism, or "diffuse intrusion". The core has a chemical composition intermediate between truly granitic and ophiolitic. Although the structure of the parent rock is not preserved in the core, important relict mineral phases of the ophiolitic rock are still present as groundmass of the porphyritic granite and as inclusions in the porphyroblastic orthoclases.

The various growth stages of the feldspars can be understood best by accepting a metasomatic origin. In the core, where metasomatism is extensive, the potassium feldspars are large and idiomorphic; their crystal structure is characterized by a low Al/Si order (monoclinic orthoclase). Going outwards, while metasomatism decreases progressively in intensity, the size of the potassium feldspars decreases, they lose their idiomorphic shape, and their crystal structure is then characterized by a higher Al/Si order (triclinic orthoclase, microcline) reflecting lower temperatures of formation. Finally, the outermost effect of metasomatism is merely formation of blastic microclines in an ophiolite that is normally devoid of potassium feldspars and very poor in  $K_2O$ .

## 2. Evolution

The granite formed in a chemically and mechanically mobilized environment. In a "collection zone" at a depth of perhaps 10 km, the granite started growing through potassium-feldspar porphyroblastesis. The first stage of its kinematic evolution was characterized by great chemical mobility, and the granitized zone pursued its growth as long as metasomatic  $K_2O-SiO_2$  was supplied faster than the rate of deformation of the country rock. The anticlinal hinge of the country rock evidently was an efficient trap, and as the anticline developed the increased volume and decreased density of the granitized mass caused it to grow upward into a mushroom-shaped diapir. The diapir rose progressively toward the surface in an environment that was at first relatively plastic, then rigid. Theoretical aspects of the ascent of a buoyant granitic mass have been outlined by FYFE (1970) and models have been proposed by RAMBERG (1970) and ROBERTS (1970).

When the granite penetrated into the brittle zone, probably within 5 km of the surface, it was mylonitized and disrupted by closely spaced cross faults; it was also altered at temperatures around 300° C or lower (chloritization, sericitization, and saussuritization).

Quartz, myrmekite, albite, etc. recrystallized while aplites, kersantites and a Cu-Pb-Zn mineralization were emplaced in the open faults. This episode of recrystallization indicates a new rise of temperature, which is perhaps related to the basaltic and rhyolitic volcanism that followed the emplacement of batholithic granites in Permo-Carboniferous time throughout the Hercynian Province. At the same time, the K/Ar geochronometric clocks were reset to zero. Although dike materials, ore mineralization and volcanics are spatially associated with the Pormenaz granite, they need not be genetically related to it, because magma may have utilized the same conduits and fracture zones to reach the surface.

From porphyroblastesis to the time of unroofing, the entire evolution is no longer than about 60 m. y. Porphyroblastesis occurred no earlier than 350 m. y. ago; from several zircon concentrates, we have obtained U/Pb dates that range from 347 to 290 m. y. (LAURENT et al., 1967). Incidentally, the ophiolitic country rock is devoid of zircons, so we have concluded that the zircons formed when the metasomatizing solutions generated the potassium feldspars. The evolution ended 290 m. y. ago, because Stephanian (Upper Carboniferous) conglomerates and arkoses carry Pormenaz granite fragments.

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