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U–Pb zircon dating of granitoids from the Dora-Maira massif (western Italian Alps)

by *François Bussy*[1,2] and *Paola Cadoppi*[3]

Abstract

Among the large number of granitic intrusions within the Dora-Maira massif, several main types can be distinguished. In this study we report field, petrographic and geochemical investigations as well as zircon typology and conventional U–Pb zircon dating of plutons representing these types. The main results are as follows: the Punta Muret augengneiss is a polymetamorphosed peraluminous granite of anatectic origin. It is 457 ± 2 Ma old and represents one of the numerous Caledonian orthogneisses of the Alpine basement. All other dated granites are of Late Variscan age. The Cavour leucogranite is an evolved granite of probably calc-alkaline affiliation, dated at 304 ± 2 Ma. The dioritic and granodioritic facies of the Malanaggio diorite (auct.) are typical calc-alkaline rocks, whose respective age of 290 ± 2 and 288 ± 2 Ma overlap within errors. The Sangone and Freidour granite types have very similar alkali-calcic characteristics; their ages are poorly constrained between 267–279 and 268–283 Ma, respectively.

The new data for the Dora-Maira granites are in keeping with models of the overall evolution of the Late- to Post-Variscan magmatism in the Alpine area in terms of age distribution and progressive geochemical evolution towards alkaline melts. In a first approximation, granitic rocks across the Variscan belt seem to be increasingly younger towards the internal (southern) parts of the orogen. A Carboniferous, distensive Basin and Range situation is thought to be responsible for the magmatic activity. This tectonic context is comparable to the back-arc opening of an active continental margin. The observed southward migration of the magmatism could be linked to the roll-back of the subducting Paleotethyan oceanic plate along the Variscan cordillera.

Keywords: granite, zircon, U–Pb geochronology, Dora-Maira, Variscan, Western Alps.

Introduction

The Paleozoic Variscan belt in Europe is the result of complex, mainly collisional interactions of two super-continents: Laurasia to the North and Gondwana to the South. This consisted of an early stage of crustal thickening, followed by a Carboniferous transtensional to extentional regime, associated with high heat flow, a high temperature/low pressure metamorphism, widespread crustal anatexis, and the emplacement of huge amounts of felsic magmatic rocks, either intrusive or as volcano-sedimentary units in intracontinental basins. Contrasting geodynamic reconstructions have been proposed in the literature to explain the Variscan orogenic evolution as well as its unusual late-stage magmatic activity (e.g. BURG et al., 1994; SCHALTEGGER and CORFU, 1995; STAMPFLI, 1996 and references cited in these papers). Assuming that the petrological characteristics of magmatic suites result from processes in specific tectonic regimes, detailed mineralogical and geochemical studies, together with a precise chronology, can put additional constraints on the current genetic models. This approach is especially helpful in regions where the subsequent Alpine orogeny erased the original Variscan features necessary to our understanding of the belt. Large parts of the Variscan chain have been involved in the Alpine orogeny (see e.g. VON RAUMER and NEUBAUER, 1993), some of them being severely metamorphosed and deformed. A

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well known example is the Dora-Maira massif, since the discovery in its southern part (CHOPIN, 1984; CHOPIN et al., 1991) of coesite and pyrope-bearing schists related to very high-pressure metamorphic conditions (3 GPa) of early Alpine age.

The Dora-Maira massif outcrops as a 25 km wide by 70 km long ellipsoid located west of Torino, northern Italy (Fig. 1). It is commonly associated with the Monte Rosa and Gran Paradiso massifs under the label "internal crystalline massifs of the western Penninic Alps". All three units are large Alpine basement nappes, occurring as tectonic windows within the overlying Mesozoic, eclogite-bearing Piemonte ophiolitic nappe. The Dora-Maira massif contains a variety of igneous rocks of acidic to intermediate composition, classically attributed to the Variscan magmatic cycle. It underwent a strong Alpine tectono-metamorphic overprint, in which its pre-existing structures were almost completely erased. At least three phases of Alpine ductile deformation have been recorded, together with a complex P-T-t path evolving from eclogitic (early Alpine, Cretaceous, but see COMPAGNONI et al. (1993) for an alternative opinion) to blueschist-, then greenschist facies grade (meso-Alpine, Eocene-Oligocene). As a consequence, all radiometric ages presently available are younger than 125 Ma (see review in MONIÉ and CHOPIN, 1991), whatever the method used, with the exception of a 2000 ± 500 Ma Sm–Nd model age (TILTON et al., 1989) and the brief mention of a zircon U–Pb date of 301 ± 1 Ma for the Brossasco metagranodiorite (J.L. PAQUETTE, pers. comm. 1989, in CHOPIN et al., 1991).

In such a polymetamorphic context, the best – if not the only – way to obtain reliable magmatic crystallization ages is the U–Pb method of dating on zircon and/or other accessory minerals (e.g. monazite, xenotime), provided a careful selection of rock samples and crystals is done. In this study, six of the main granite types identified within the northern and central part of the Dora-Maira massif (Fig. 1) have been selected for U–Pb dating on the basis of their mineralogical and geochemical diversity, as well as their structural relationships with the country rocks. Sampling was done within the least deformed and metamorphically recrystallised facies of each granite type.

The aim of the study was to check the supposedly Upper Paleozoic age of the rocks; then test in the Dora-Maira massif a number of current statements and models on the general evolution of the Variscan orogeny, in particular a correlation of age with magma composition, which often evolves from calc-alkaline to alkaline; and a correlation of both age and chemistry with the geographical position of the plutons within the Western European part of the belt. Conversely, new constraints on the pre-Mesozoic paleogeographic position of the Dora-Maira massif might be obtained.

Geological framework

The Dora-Maira massif consists of a complex assemblage of crustal slices of Paleozoic rocks, separated by low-angle Alpine thrust faults and/or narrow intercalations of Mesozoic material (VIALON, 1966; MICHARD, 1967; BORGHI et al., 1984; CHOPIN et al., 1991; SANDRONE et al., 1993). The Paleozoic basement includes (Fig. 1):

1) a pre-Carboniferous, polymetamorphic unit mainly composed of garnet-chloritoid micaschists, associated with impure marbles and a few bodies of metabasites and granitoids of granodioritic composition ("gneiss amygdalaires", VIALON, 1966). Relics of pre-Alpine, medium to high temperature metamorphic assemblages, are rarely preserved in the micaschists (muscovite, garnet and pseudomorphs after staurolite, BORGHI et al., 1985; CADOPPI, 1990a; sillimanite, BOUFFETTE et al., 1993; COMPAGNONI et al., 1993) and in the granitoids (red biotite, muscovite, plagioclase and garnet, COMPAGNONI and SANDRONE, 1981; CADOPPI, 1990 a, b);

2) several monometamorphic, detrital sequences, thought to be of Carboniferous, respectively Permian age. They comprise graphite-bearing metasediments (micaschists, meta-arenites, metaconglomerates and quartzites: the Pinerolo Graphitic Complex; «Ensemble graphitique de Pinerolo», VIALON, 1966), fine-grained albite gneisses and micaschists ("gneiss minuti"; "faciès devenant charbonneux", VIALON, 1966), chloritoid ± garnet micaschists and impure quartzites (SANDRONE et al., 1993).

Magmatic rocks are widespread in both mono- and polymetamorphic unit types. Most of them are intrusives with an intermediate to granitic composition, although basic types are also present. Volcanic rocks are restricted to the southernmost part of the massif (Maira valley) as rare rhyolitic and mafic horizons interlayered within Permo-Carboniferous(?) metasediments (BONIOLI et al., 1992; BALESTRO et al., 1995).

The granitic rocks

Several types of plutonic rocks have been distinguished on the basis of their chemistry, texture and structural position (VIALON, 1966; SANDRONE

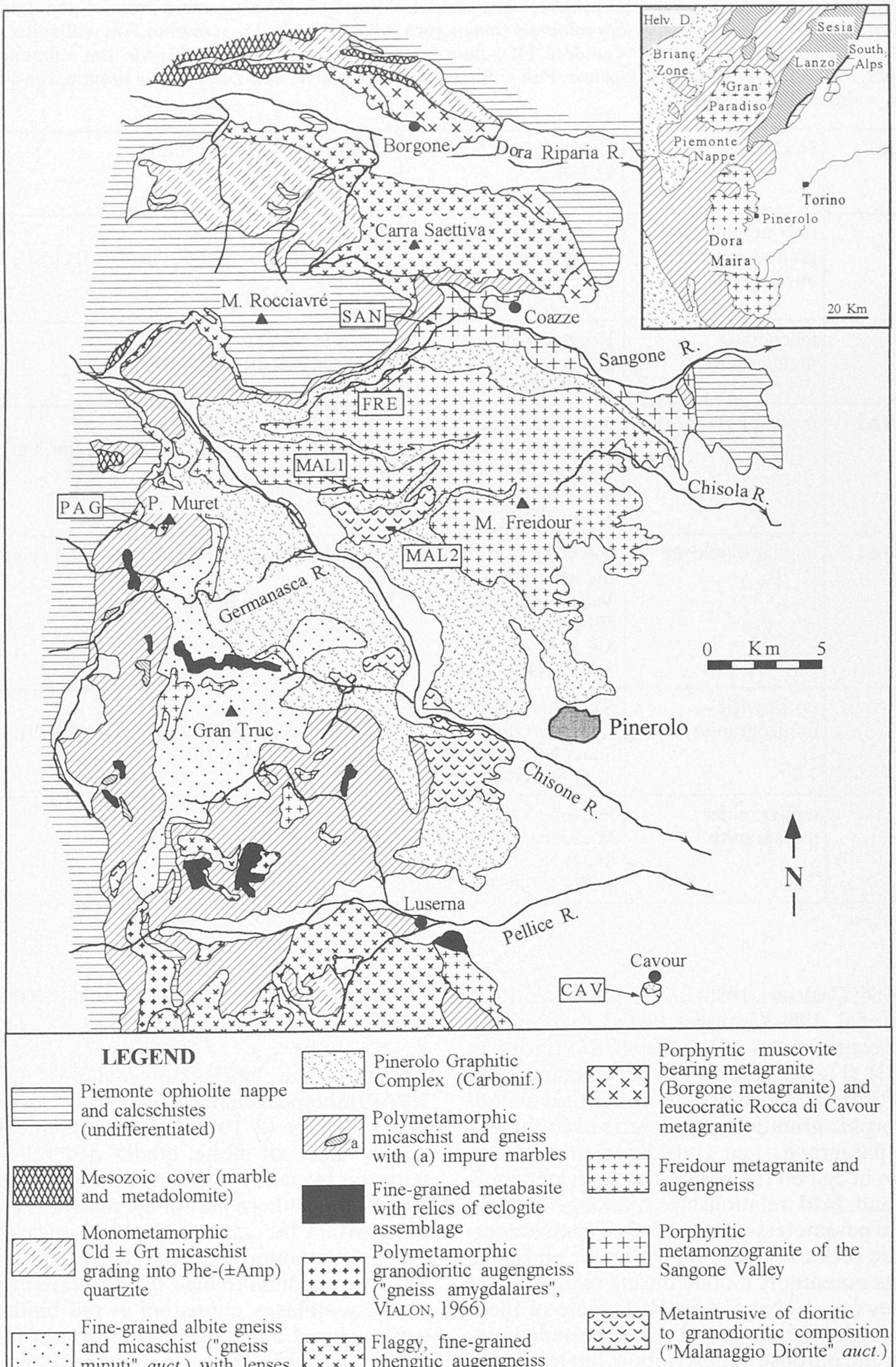

Fig. 1 Geological map of the northern and central Dora-Maira massif and sample location (from SANDRONE et al., 1993).

Tab. 1 Sample location and description. Abbreviations: MR = magmatic relics (as main primary minerals), MM = metamorphic minerals, ACC = accessory minerals (magmatic), Ab = albite, Act = actinolite, Aln = allanite, Ap = apatite, Bt = biotite, Chl = chlorite, Ep = epidote, Flt = fluorite, Grt = garnet, Hbl = hornblende, Ilm = ilmenite, Kfs = K-feldspar, Ms = muscovite, Pl = plagioclase, Phe = phengite, Qtz = quartz, Rt = rutile, Tnt = titanite, Tur = Tourmaline, Zrn = zircon, Zo = zoisite.

Sample	Rock type	Location and U.T.M. coordinates	Mineralogical composition
PAG	polymetamorphic granodioritic augengneiss	Germanasca Valley, Punta Muret Sheet N° 67 IV N.E. 32TLQ501809	MR: Kfs MM: Pl, Qtz, red Bt, Ms, Phe, Grt I, Grt II, Zo, Ep, Tnt, Ilm ACC: Ap, Zrn, Aln
CAV	leucocratic metagranite	Rocca di Cavour Sheet N° 67 II N.E. 32TLQ716598	MR: Kfs, Ms (?) MM: Ab, Qtz, Bt, Phe, Ep, Chl ACC: Grt, Zrn, Ap, Aln, Tnt
"Malanaggio diorite" MAL1	meta-quartz-diorite	Northern slope of the lower Chisone Valley – Bric Blecié. Sheet N° 67 IV N.E. 32TLQ579824	MR: Hbl (very scarce) MM: Act, Chl, Bt, Ab, Qtz, Zo, Rt, Ilm, Tnt ACC: Zrn, Ap, Aln
"Malanaggio diorite" MAL2	metagranodiorite	Northern slope of the lower Chisone Valley – Albarea Village Sheet N° 67 I N.O. 32TLQ599803	MR: Kfs, Qtz, (Pl), Bt (well preserved magmatic texture) MM: Ab, Zo, Ep, Bt, Chl ACC: Zrn, Ap, Aln, Tnt
SAN	porphyritic monzogranite	Sangone Valley, Centrale Olivoni Sheet N° 55 II 5. O. 32TLQ626896	MR Kfs, Qtz, Bt MM: Ab, Qtz, Phe, Bt, Zo, Ep, Grt, Chl, Tnt ACC: Zrn, Ap, Aln, Tur
FRE	equigranular metagranite	Sangone Valley, Madonna di Lourdes Sheet N° 55 II 5. O. 32TLQ614881	MR: Kfs MM: Ab, Qtz, Phe, Bt, Ep, Grt, Chl, Tnt ACC: Aln, Zrn, Ap, Flt

et al., 1986; CADOPPI, 1988; SANDRONE et al., 1988; BORGHI et al., 1989; CADOPPI, 1990a). In the northern and central parts of the massif, SANDRONE et al. (1993) (Fig. 1) identified a polymetamorphic granodioritic augengneiss, as well as six monometamorphic granitic types, described in the following paragraphs and considered to be Late-Variscan in age on the basis of texture, metamorphism and field relationships. Among the geochemical parameters classically used to characterize acidic rocks, several refer to major and trace elements potentially mobile during metamorphic processes (e.g. K, Na, Ca, Sr, Rb). Some of these sensitive parameters have been reported thereafter for the purpose of description, but less sensitive features such as zircon morphology or HFS-element geochemistry have been preferably used to establish the typology of the investigated granite types.

THE POLYMETAMORPHIC AUGENGNEISS (PAG)

Known as the "gneiss amygdalaires" (VIALON, 1966), this type is characterized by an augen structure with large (2–10 cm), polycrystalline nodules mainly made of albite, quartz and relics of K-feldspar. It mainly outcrops in the Pellice valley and in the southern part of the massif, as a distinct body within the garnet-chloritoid micaschists of the polymetamorphic unit. Relics of probably Variscan, medium to high-temperature metamorphic assemblages, consisting of red biotite, muscovite, garnet and plagioclase (SANDRONE et al., 1986; CADOPPI, 1990 a, b) survived the strong Alpine metamorphic overprint and suggest a pre-Variscan intrusion age.

The gneiss sample PAG (Tab. 1) was taken in a small outcrop in the southern slope of Punta

Muret, Germanasca valley (BORGHI et al., 1985; CADOPPI, 1990 a, b; BOUFFETTE et al., 1993). No evidence for contact metamorphism was found in the surrounding micaschists. A penetrative foliation is marked by pre-Alpine muscovite and red biotite, altered into phengite ± Ti(-Fe)-rich phases ± garnet. The protolith was probably a peraluminous granodiorite, considering the A/CNK ratio of 1.12 and the presence of normative corundum (Tab. 2 and Fig. 2) (with the reservation relative to the mobility of Ca, Na and K). In comparison with the granodioritic facies of the "Malanaggio diorite" (sample MAL2, Tab. 2), PAG displays higher Zr, Th and total REE contents (Fig. 3), as well as a higher Rb/Sr ratio, which points to contrasting source materials. Zircons show a well-defined population in the typological diagram of PUPIN (1980) (Fig. 4), restricted to subtypes characterized by low mean T and mean A indices, i.e. with a preferential development of {211} and {110} crystallographic forms. According to PUPIN (1980, 1988) (Fig. 5), this kind of zircons is typical of granites of crustal anatectic origin, which agrees well with the peraluminous character of the rock.

THE CAVOUR METAGRANITE (CAV)

This garnet-muscovite-bearing leucocratic metagranite constitutes the "Rocca di Cavour" inselberg within the Po sedimentary plain (Fig. 1). It is in contact with fine-grained, locally biotite-rich micaschists and gneisses, thought to belong to the Pinerolo Graphitic Complex (VIALON, 1966), but the nature of the contact is unclear.

Sample CAV (Tab. 1) was collected along the main road to the top of the inselberg. It is a weakly deformed equigranular rock with rare relics of magmatic(?) muscovite and scattered euhedral garnet crystals, which plots in the alkali-granite field of the R_1R_2 diagram of LA ROCHE et al. (1980) (Fig. 2). Mineralogical and geochemical evidences all point to a crystallization from a highly differentiated felsic magma, such as its high silica content (74% SiO_2, Tab. 2) and Rb/Sr ratio, and low Zr concentration. The presence of muscovite and garnet, a relatively low whole-rock REE content, a moderate La/Yb ratio (= 8.96), and a pronounced Eu anomaly are typical features of evolved, leucocratic monzogranitic magmas as exemplified by COCHERIE (1984) and ROSSI (1986) in the Late-Variscan calc-alkaline batholith of Corsica. The zircon morphology (Fig. 4) also points to a highly differentiated magma with S2–5, L2–5 and G1 subtypes, which, according to PUPIN (1988) (Fig. 5), is consistent with a calc-alkaline affiliation.

Tab. 2 Chemical composition of the analysed samples. REE, U, Th and Y were analysed by ICPMS by XRAL laboratories, Don Mills, Canada; others elements by X-ray fluorescence. FeO concentrations have been measured by colorimetry and CO_2 by coulometry. H_2O concentrations were determined from loss on ignition.

	PAG	CAV	MAL1	MAL2	SAN	FRE
Major elements (wt%)						
SiO_2	65.79	73.96	58.04	68.25	70.46	73.06
TiO_2	0.78	0.14	1.29	0.36	0.40	0.32
Al_2O_3	15.07	13.56	17.37	15.21	14.21	13.76
Fe_2O_3	1.89	0.51	1.86	1.03	(*)3.25	(*)2.54
FeO	3.17	1.14	4.08	1.95	n.a.	n.a.
MnO	0.07	0.03	0.09	0.05	0.05	0.04
MgO	1.34	0.38	3.27	1.60	0.75	0.48
CaO	2.12	0.12	6.72	3.55	1.61	1.62
Na_2O	3.21	3.70	3.23	3.76	3.58	3.62
K_2O	3.98	4.54	1.40	2.61	4.44	4.16
P_2O_5	0.19	0.04	0.26	0.08	0.19	0.14
H_2O	1.28	0.70	1.26	0.67	0.79	0.60
CO_2	0.21	0.28	0.26	0.24	n.a.	n.a.
Trace elements (ppm)						
Ba	713	502	398	669	553	536
Rb	150	159	51	85	202	157
Sr	192	75	376	382	139	102
Pb	22	9	4	16	n.a.	n.a.
Th	18.5	16.8	7.2	15.5	16	19
U	4.5	6.3	2.5	7.7	n.a.	n.a.
Nb	25	14	11	10	11	9
Y	38	20	20	12	36	37
Zr	251	91	83	92	210	171
V	72	8	214	64	35	12
Cr	35	< 3	37	30	16	8
Ni	15	< 2	5	4	13	7
Co	36	42	30	35	n.a.	n.a.
Zn	83	26	62	44	53	48
Ga	19	14	18	14	19	16
REE (ppm)						
La	49.7	25.1	21.8	27.7	32.0	44.0
Ce	99.8	49.7	45.2	51.5	70.0	94.0
Pr	11.5	5.4	5.4	5.6	n.a.	n.a.
Nd	44.6	19.1	22.0	19.6	28.0	37.0
Sm	11.6	4.7	6.0	4.4	6.6	7.5
Eu	1.38	0.39	1.20	0.74	1.07	0.92
Gd	9.1	4.0	4.9	3.2	5.9	6.4
Tb	1.3	0.6	0.7	0.5	n.a.	n.a.
Dy	7.9	4.0	4.3	2.5	5.6	5.7
Ho	1.52	0.78	0.81	0.47	n.a.	n.a.
Er	4.4	2.5	2.3	1.4	3.1	3.1
Tm	0.6	0.4	0.3	0.2	n.a.	n.a.
Yb	4.0	2.8	2.1	1.5	3.0	3.1
Lu	0.56	0.41	0.29	0.24	0.53	0.51
A/CNK	1.12	1.21	0.91	0.98	1.04	1.03
norm C	2.49	2.55	0.00	0.39	0.97	0.63

(*) Fe_2O_3 as total Fe
n.a. = not analyzed
norm C = normative corundum (wt%)

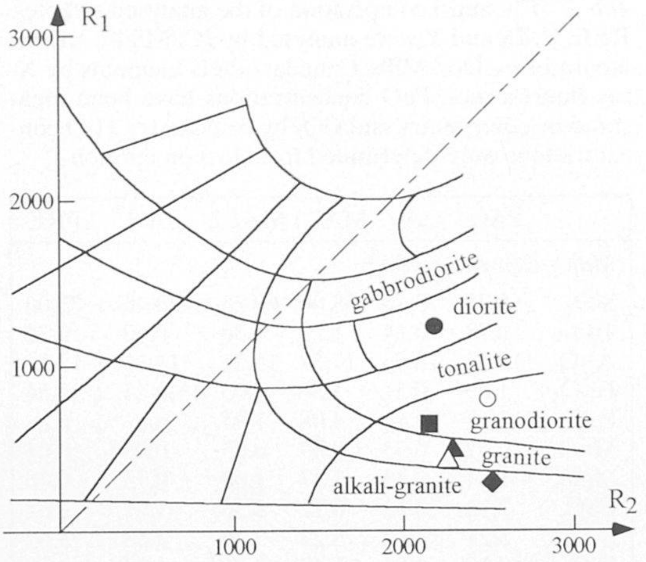

Fig. 2 Cumulative R_1-R_2 diagram (DE LA ROCHE et al., 1980) for the analyzed granitoids. Symbols: ■ = polymetamorphic granodioritic augengneiss (PAG); ◆ = Cavour leucocratic metagranite (CAV); △ = Freidour metagranite (FRE); ▲ = porphyritic metamonzogranite of the Sangone Valley (SAN); ● = dioritic gneiss (MAL1) belonging to the "Malanaggio Diorite"; ○ = metagranodiorite (MAL2) belonging to the "Malanaggio Diorite".

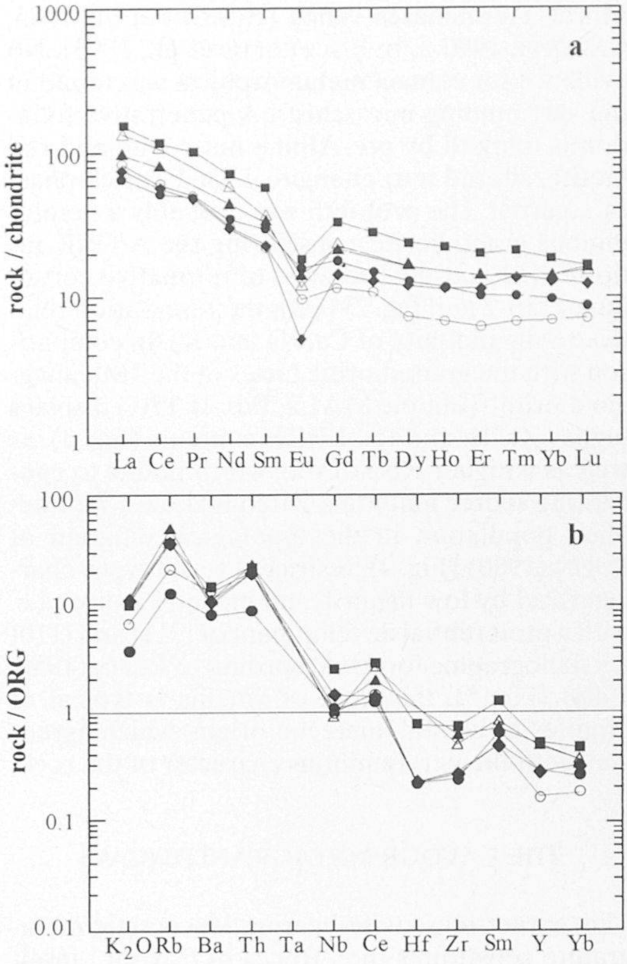

Fig. 3 a) REE patterns for the analyzed samples. Normalization values from HASKIN et al. (1968) and NAKAMURA (1974); symbols as in figure 2; b) Ocean-ridge granite (ORG)-normalized (PEARCE et al., 1984) spidergram; symbols as in figure 2.

THE SANGONE METAGRANITE (SAN)

This is a porphyritic monzogranite, which outcrops in the lower slopes of the Sangone and Sangonetto valleys (Fig. 1). Contacts are magmatic with the overlying polymetamorphic garnet-chloritoid micaschists and tectonic with the underlying graphite-bearing metasediments of the Pinerolo Graphitic Complex. Magmatic textures and mineralogy (Tab. 1) are rather well preserved, despite a locally pervasive mylonitic foliation (CADOPPI, 1988, 1990a) and a metamorphic crystallisation of phengite, albite, zoisite, garnet and quartz.

Sample SAN is a poorly foliated rock collected near the Sangone river. It plots in the granite field of the R_1R_2 diagram (Fig. 2) and has a A/CNK ratio of 1.04. This rock displays geochemical features of an alkali-calcic (in the sense of PEACOCK, 1931) monzogranite (Tab. 2, Fig. 3). Its alkaline affinity is evidenced by relatively high P, Ti, Zr and Y contents and its zircon morphology. The latter display a high mean A index, i.e. a {101} pyramid largely dominant over {211} (Fig. 4), which is interpreted by PUPIN (1988) as typical of "subalkaline" (i.e. alkali-calcic) granitoids. On the other hand, the biotite chemistry (CADOPPI, 1990a) has a clear calc-alkaline affinity (NACHIT et al., 1985); but this feature is potentially sensitive to metamorphic overprints (see e.g. BUSSY, 1990) and cannot be safely taken into account.

THE FREIDOUR METAGRANITE (FRE)

This is a large body outcropping in the Chisone and Sangone valleys, in which magmatic textures and parageneses are locally preserved. The main type is an equigranular, allanite-rich granite with aplitic dikes and scattered biotite-rich, fine-grained enclaves. Country rocks are extensively albitized near the contact (CADOPPI et al., 1993a); they consist of graphite-bearing micaschists, metaconglomerates and fine-grained gneisses belonging to the Pinerolo Graphitic Complex.

Sample FRE was collected in the upper Sangone valley, close to the "Madonna di Lourdes" sanctuary, near Forno di Coazze (Fig. 1). Except for the texture, this equigranular rock is mineralogically very similar to the porphyritic Sangone-type, with a higher allanite content and less biotite (CADOPPI, 1990a). The latter has been totally replaced by metamorphic aggregates of phengite + titanite ± clinozoisite. From a geochemical point of view, FRE is comparable to SAN, but slightly more differentiated with higher LREE values and a larger Eu anomaly (Tab. 2, Figs 2, 3). Zircons are also very similar (Fig. 4); the mean points of FRE and SAN plot together in the subalkaline field of PUPIN (Fig. 5).

THE "MALANAGGIO DIORITE" (MAL)

The so-called "Malanaggio diorite" (auct.) includes a series of dioritic to granodioritic gneissic bodies, which intrude the Pinerolo Graphitic Complex in the lower Chisone valley. Scattered pseudomorphic aggregates after andalusite in the graphitic schists (FRANCHI and NOVARESE, 1895; CADOPPI et al., 1995) are attributed to a thermal contact metamorphism. Minor metadioritic bodies are also found within the polymetamorphic unit in the Pellice valley (SANDRONE et al., 1988) and in the southernmost part of the massif (Maira valley) (CADOPPI et al., 1993b; BALESTRO et al., 1995). Two samples were collected for geochronological work.

Sample MAL1 comes from an outcrop located north of Perosa Argentina (Fig. 1). This foliated, fine-grained dioritic gneiss displays a secondary metamorphic assemblage of actinolite + biotite + chlorite + albite + zoisite + quartz, as well as rare relics of magmatic hornblende (Tab. 1). MAL1 plots in the diorite field of the R_1-R_2 diagram (Fig. 2) and shows typical calc-alkaline geochemical features (Tab. 2 and Fig. 3), including a moderately fractionated REE pattern.

Sample MAL2 is a more acidic variety of the "Malanaggio diorite", collected in a small outcrop near the village of Albarea (ZANETTIN-LORENZONI, 1967; MENSIO, 1992). This granodioritic to tonalitic gneiss displays rather well preserved magmatic textures and mineral assemblages (see

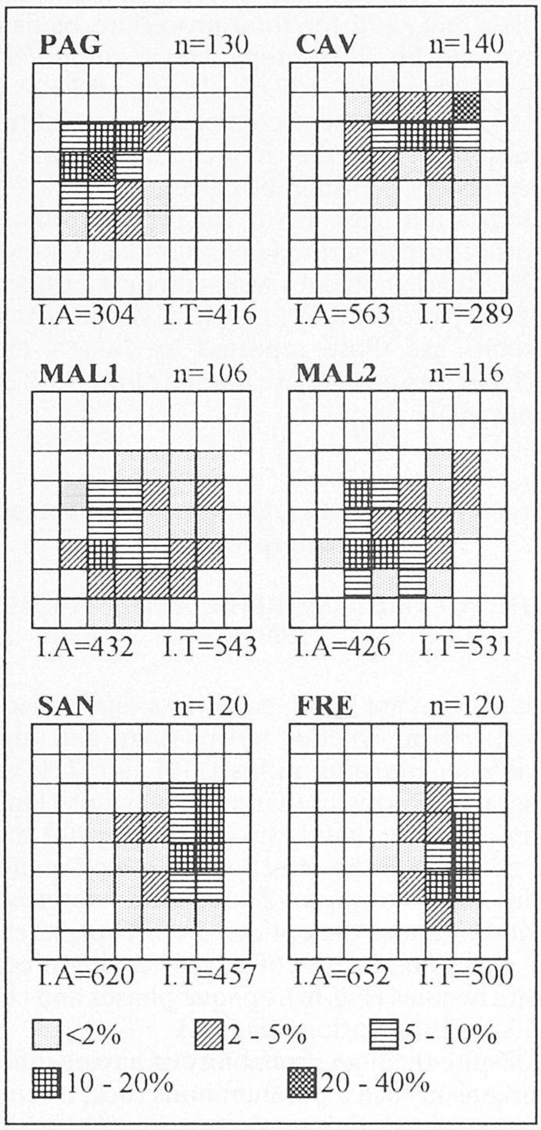

Fig. 4 Typologic distribution diagrams and A/T coordinates (PUPIN, 1980) for the analyzed samples. n is the number of zircons for each sample.

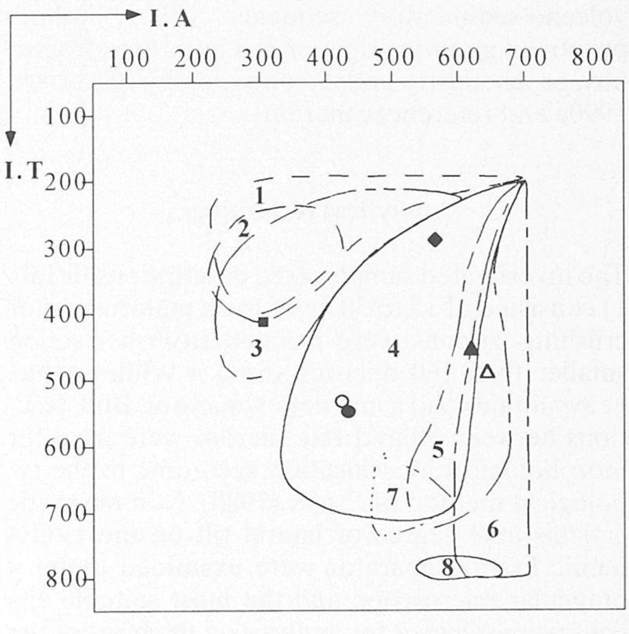

Fig. 5 Mean A/T points in the classification diagram of PUPIN (1988). 1 = aluminous granites; 2 = (sub)autochthonous monzogranites-granodiorites; 3 = intrusive aluminous monzogranites-granodiorites; 4 = calc-alkaline and K calc-alkaline series granites; 5 = subalkaline series granites; 6 = alkaline series granites; 7 = continental tholeiitic granites; 8 = oceanic tholeiitic series granites. Symbols as in figure 2.

Tab. 1). The magmatic hornblende is totally replaced by aggregates of fine-grained biotite. As for MAL1, geochemical data point to a calc-alkaline rock. Both samples display very similar zircon morphologies (Fig. 4) with a wide variety of S subtypes, typical for calc-alkaline series granitoids (Fig. 5).

THE BORGONE AND "PIETRA DI LUSERNA" METAGRANITES

These two granite types have not yet been dated, but they are briefly mentioned here as part of the present inventory. The Borgone metagranite is a porphyritic to equigranular, slightly peraluminous, two-mica rock (CADOPPI, 1990a) mainly outcropping in the lower Susa valley. It is grading into a phengite-rich leucocratic gneiss with increasing deformation and metamorphic recrystallisation. Its relationships with the metapelitic country rocks are still unclear.

The "Pietra di Luserna" refers to a heterogeneous series of flaggy, leucocratic gneisses, partly porphyritic and phengite-rich, partly tourmaline-rich, and of "silvery" phengitic schists. This complex forms a flat body structurally located at the top of the Dora-Maira massif, in tectonic contact with the surrounding units. Whereas VIALON (1966) considers these rocks as a metamorphosed volcano-sedimentary sequence, other authors propose a granitic origin on the basis of petrography, geochemistry and zircon typology (CADOPPI, 1990a and references therein).

Analytical techniques

The investigated samples (see descriptions in Tab. 1) consisted of 15 to 30 kg of fresh material. After crushing, zircons were isolated from a fraction smaller than 160 microns, using a Wilfley table, heavy liquids and a magnetic separator. Bulk fractions between 50 and 160 microns were used for morphological identification according to the typological method of PUPIN (1980). Non magnetic crystals at 0 degree of lateral tilt on the Isodynamic Frantz separator were examined under a binocular microscope and the most suitable zircons were selected for analysis on the basis of the following criteria: high transparency, lack of mineral inclusions and cracks, euhedral shape, absence of coloration or weakest coloration. In order to minimise the incorporation of inherited lead, special attention was given to crystals showing central, tubular melt inclusions (e.g. Fig. 6a) and to very thin needle-like prisms, as they are mostly free of old zircon cores. Analyzed multi-grain fractions were homogeneous in terms of morphology and length/width ratio. Air-abrasion was applied systematically to reduce or eliminate surface-correlated lead loss and younger overgrowths (KROGH, 1982). Dissolution and chemistry were carried out using the standard techniques outlined in KROGH (1973), using a mixed ^{205}Pb–^{235}U spike (KROGH and DAVIS, 1975; PARRISH and KROGH, 1987), except that the capsule and column size were reduced by a factor of 10. U and Pb were loaded together with silica gel and phosphoric acid on single Re filaments, and measured in sequence on a VG 354 mass spectrometer in single collector operating mode and using a Daly photomultiplier detection system.

Measured ratios were corrected for instrumental mass fractionation of +0.1% per atomic mass unit (a.m.u.), for a Daly mass bias of 0.37%/a.m.u., and for total procedure blanks of 0.8 to 5 pg Pb (Pb isotopic composition $^{208}Pb : ^{207}Pb : ^{206}Pb : ^{204}Pb = 37.62 : 15.56 : 18.3 : 1$) and 0.1 pg U. When present, common Pb was subtracted according to the model of STACEY and KRAMERS (1975) using the calculated $^{207}Pb/^{206}Pb$ crystallization ages. Error calculations followed the procedure described in CORFU and GRUNSKY (1987). Regression lines were computed using the ISOPLOT program of LUDWIG (1988) and decay constants are those reported by JAFFEY et al. (1971). Errors on ages are quoted at the 95% confidence level.

Zircon characteristics, U–Pb analytical results and interpretation

THE POLYMETAMORPHIC AUGENGNEISS (PAG)

Most zircons are clear, colourless and euhedral, with a typical igneous morphology and highly variable length/width ratios. {110} and {211} crystallographic forms are largely dominant (Fig. 4). Edges are often slightly smoothed (Fig. 6b), a feature ascribed to the effect of the Variscan and/or Alpine metamorphism. Zoning and overgrowths are absent under the optical microscope, whereas rare inclusions consist of inherited zircon cores, apatite needles (Fig. 6f), opaque phases and channel-like melt inclusions (Fig. 6a).

Despite the high probability of having inherited zircons in such a peraluminous rock, three out of four selected multi-grain fractions (1 to 3, Tab. 3) are apparently devoid of any old component, as they are analytically concordant at the same age within errors (Fig. 7a). Considering the preserved

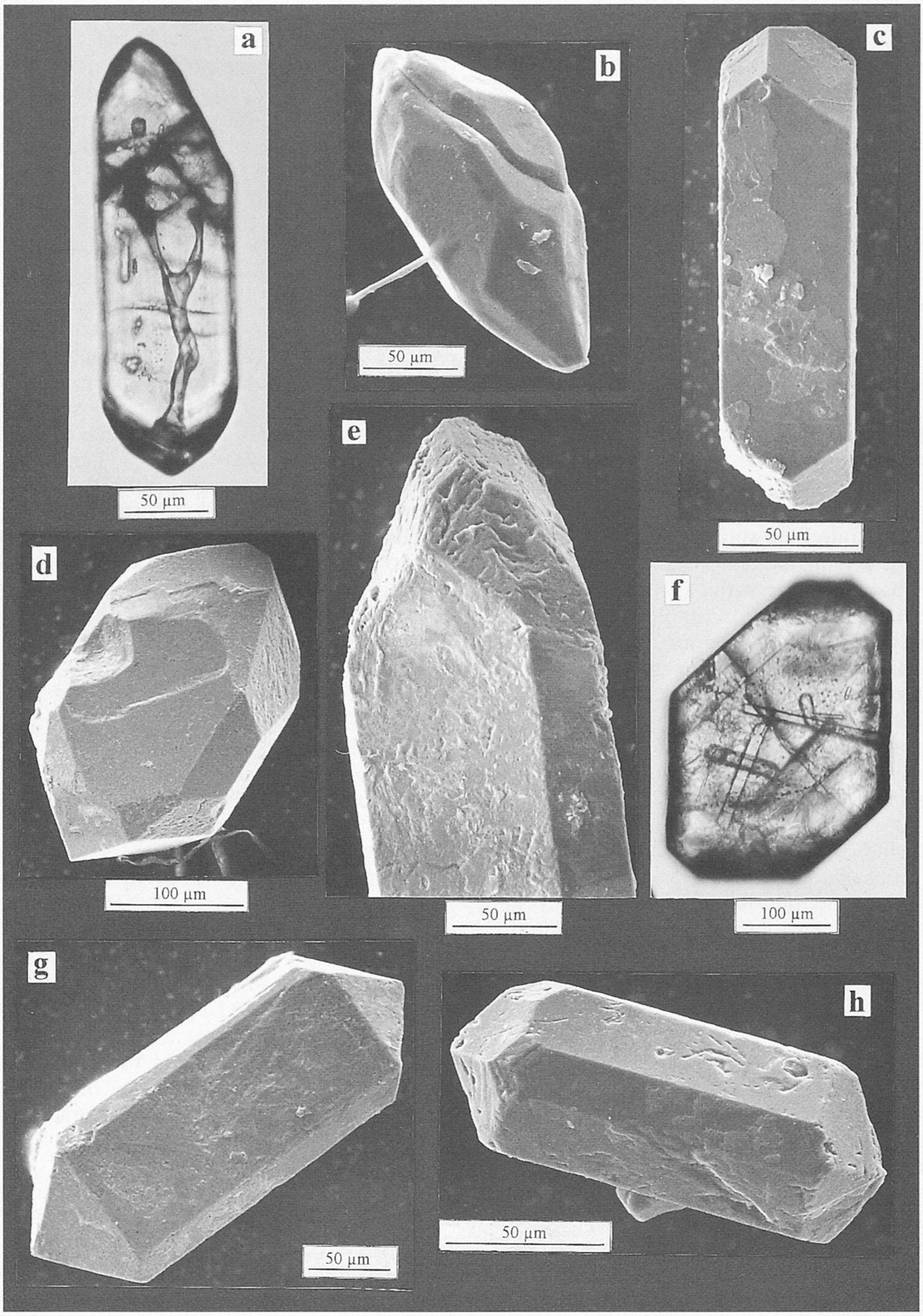

Fig. 6 Microphotographs of zircons from the sampled rocks. a) PAG – Transmitted-light photomicrograph of a sub-euhedral S_7 subtype with channel-like cavities; b) PAG – Scanning electron microscope (SEM) image of a S16 subtype with smoothed edges and corners; c) CAV – SEM image of a euhedral, low-T subtype (G1); d) MAL2 – SEM image of an euhedral S19 subtype; e) MAL1 – SEM image of an elongated S17 subtype with pitted faces (in particular the pyramidal ones); f) FRE – Transmitted-light photomicrograph of a euhedral S24 subtype with needle-like apatite inclusions; g) FRE – SEM image of a euhedral crystal with alkaline morphology (P4); h) SAN – SEM image of a euhedral S20 subtype.

igneous morphology of the zircons and the good reproducibility of the data, we propose a mean U–Pb age of 457 ± 2 Ma for the crystallization of the granitic protolith of the Punta Muret polymetamorphic augengneiss. Fraction (4) consisted of 16 small prisms and displays a significantly lower radiogenic Pb concentration as compared to (1)-(3) (8 versus 23 to 39 ppm); it yielded slightly older, discordant isotopic ages ($^{207}Pb/^{206}Pb$ age of 475 Ma), attributed to the presence of an inherited component.

THE CAVOUR GARNET-MUSCOVITE METAGRANITE (CAV)

Sample CAV yielded euhedral, mostly sharp faceted, elongated (l/w >> 2) zircons. {110} and {211} are the best developed crystallographic forms, when not the only ones present, as in the commonly found G1 subtype (PUPIN, 1980) (Fig. 6c). Most crystals are colourless, with occasional yellow-brown overgrowths. Inclusions are of the same type as reported for sample PAG; relic cores are rarely visible. Indeed, none of the four selected multi-grain fractions (5 to 8, Tab. 3, Fig. 7b) seems to include inherited lead. They plot together on the Concordia diagram at very similar U–Pb ages ranging from 299.6 ± 1.4 to 304.3 ± 2.6 Ma. Fractions (5), (6) and (7) are analytically concordant and overlap within errors at a mean U–Pb age of 304 ± 2 Ma. (8) records a slight lead loss episode incompletely eliminated by abrasion. The Th/U ratios of the zircons (0.41–0.56) are the highest calculated within the present study, but there is no obvious correlation with the whole-rock Th/U values (Tab. 2). 304 ± 2 Ma is interpreted as the crystallization age of the Cavour leucogranite.

THE SANGONE METAMONZOGRANITE (SAN)

Zircons of sample SAN are clear, pale violet, sharp faceted prisms without any trace of resorption. P subtypes (absence of {211} pyramid) are very dominant (Figs 4 and 6g). Inclusions consist of apatite needles and opaque minerals. Zircons of low T index (e.g. S_5, P_1), considered by PUPIN (1980) to be late-magmatic, are partly metamict (suggesting a high uranium content) and display features such as overgrowths, dark-brown colours, zoning, and turbidity.

The few good-quality zircons extracted from sample SAN were shared out into five fractions of contrasting morphologies (9 to 13, Tab. 3). None of them is perfectly concordant, but four (9–11 and 13) are grouped near the Concordia curve at 266–268 Ma (Fig. 7c). The fifth (12) displays higher ages ($^{207}Pb/^{206}Pb$ age of 424 Ma) and must contain an inherited component. Fraction (9) is 2% discordant, but overlaps the Concordia curve within errors at U–Pb ages of 267.9 ± 1.2 and 268.4 ± 1.4 Ma, respectively. (9) is free of any inherited core, as it consisted only of prisms with a hollow central channel open at both crystal ends. In other words, a mean U–Pb date of 268 ± 1.2 Ma is a possible age for the crystallization of the Sangone metagranite protolith. Nevertheless, it cannot be ruled out that (9) records a slight lead loss incompletely removed by abrasion. Such a loss is apparent in fractions (10) and (13), which plot slightly below (9) on the Concordia diagram. If this assumption is true, the age of the system would rather be the upper intercept value of the discordia line defined by (9), (10), (13) and a point on the Concordia representing the lead loss event. However, fraction (10) records a slight inheritance in addition to a lead loss, as does (11) in a more pronounced way. The best way to estimate the upper age limit is therefore to project (9) and (13) up on the Concordia curve from about 30 Ma, if one assumes that the meso-Alpine metamorphism is responsible for the lead loss event. Although this assumption is not directly documented by U–Pb data, petrologic observations in the northern part of the Dora-Maira massif show that the meso-Alpine tectono-metamorphic overprint (i.e. upper greenschists to amphibolite facies conditions in the Chisone and Sangone valleys, CADOPPI et al., 1995) is much stronger than the older, scarcely recorded eo-Alpine high-pressure event; it is therefore more likely to have disturbed the zircon isotopic system. This interpretation is supported by a perfect $^{40}Ar/^{39}Ar$ biotite plateau age of 31.8 ± 0.1 Ma for the Malanaggio granodiorite (i.e. sample MAL2) (CADOPPI et al., 1994). If the projection point is set at 30 ± 10 Ma, the upper intercept age is 274 +5/–4 Ma. In summary, we suggest that the crystallization age of the Sangone metagranite is within the time range of 267 to 279 Ma.

THE FREIDOUR METAGRANITE (FRE)

Like for mineralogical and geochemical features, the Freidour metagranite is very similar to the Sangone type in terms of zircon morphology and typological distribution (Figs 4 and 6 g, h). P subtypes are even more abundant than in SAN sample, representing more than 60% of the total population. The four analysed multi-grain fractions (14 to 17, Tab. 3) do not allow a precise age determination (Fig. 7d), because data do not overlap

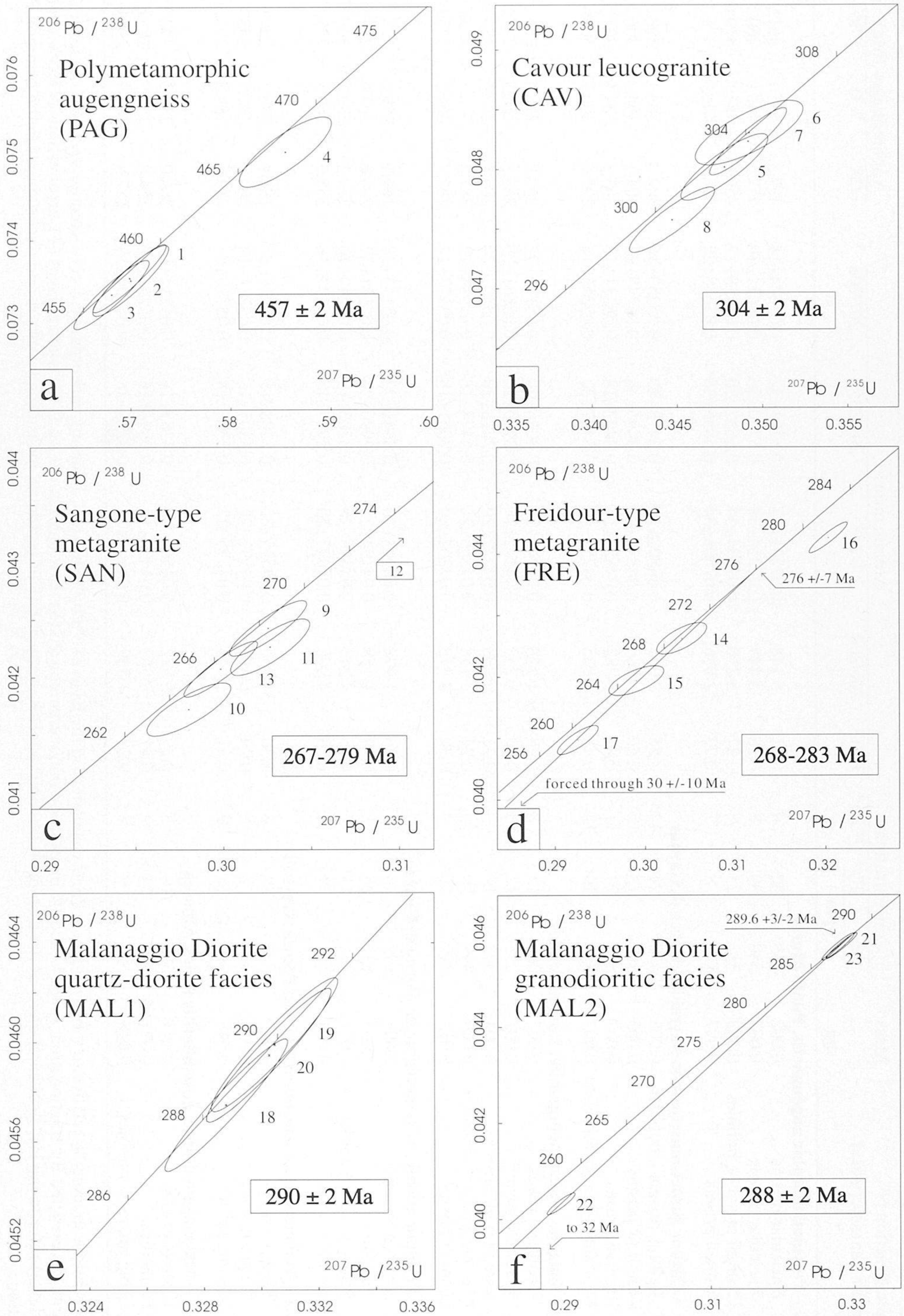

Fig. 7 *a–f*) U–Pb concordia diagrams for the analyzed granitic samples; fraction numbers refer to table 3, ellipses are 2 sigma errors and the preferred ages are framed, see text for discussion.

Tab. 3 U–Pb isotopic data on zircons extracted from the investigated granites.

Sample (fraction N° and grain characteristics)	Mass	Concentrations			Th/U	206/204	Atomic ratios			Apparent ages (Ma)		
		U	Pb*	^{208}Pb*			206/238	207/235	207/206	6/38	7/35	7/6
	mg	ppm		a	b	c	d	d	d			
PAG – Polymetamorphic augengneiss, Punta Muret												
1 6 acicular prisms	0.002	443	32	9	0.31	5 146	0.07351±34	0.5701±32	0.05624±14	457.3	458.1	461.9
2 7 acicular prisms	0.003	540	39	8	0.28	8 447	0.07354±34	0.5700±30	0.05621±10	457.5	458.0	460.7
3 12 small prisms + bubbles	0.003	313	23	8	0.27	5 210	0.07334±34	0.5682±30	0.05618±12	456.3	456.8	459.6
4 16 small prisms	0.007	110	8	7	0.23	2 086	0.07506±34	0.5856±38	0.05658±22	466.6	468.0	475.1
CAV – Cavour garnet-muscovite metagranite, Rocca di Cavour												
5 4 elong. prisms + bubbles	0.003	472	24	14	0.55	3 365	0.04802±22	0.3478±20	0.05253±16	302.3	303.1	308.5
6 4 hollow prisms	0.003	342	18	15	0.56	+860	0.04830±22	0.3495±36	0.05247±42	304.1	304.3	306.1
7 10 small prisms	0.007	460	23	11	0.41	10 783	0.04823±24	0.3492±18	0.05251±10	303.7	304.1	307.5
8 12 prisms + cracks/bubbles	0.007	375	19	12	0.44	+1 905	0.04758±22	0.3447±20	0.05255±14	299.6	300.7	309.4
SAN – Sangone monzometagranite, Sangone valley												
9 5 hollow prisms	0.007	366	15	8	0.28	1 878	0.04243±20	0.3026±20	0.05172±22	267.9	268.4	273.1
10 4 tabular prisms	0.005	275	12	8	0.27	1 253	0.04172±18	0.2980±20	0.05181±20	263.5	264.9	277.0
11 9 small pink prisms	0.004	393	17	9	0.31	2 088	0.04223±20	0.3028±20	0.05201±20	266.6	268.6	285.9
12 12 elong. prisms + bubbles	0.009	449	20	8	0.24	7 158	0.04558±22	0.3474±18	0.05528±10	287.3	302.7	423.5
13 22 small prisms	0.015	390	16	9	0.30	3 943	0.04207±20	0.3001±18	0.05173±12	265.7	266.5	273.6
FRE – Freidour allanite-rich metagranite, Forno di Coazze												
14 3 hollow prisms	0.005	199	8	7	0.26	1 978	0.04263±20	0.3041±22	0.05173±28	269.1	269.6	273.7
15 7 needles	0.003	632	26	8	0.29	1 158	0.04194±20	0.2990±24	0.05171±32	264.8	265.6	272.6
16 5 big prisms + bubbles	0.011	292	13	7	0.25	7 243	0.04426±20	0.3203±18	0.05249±10	279.2	282.2	306.8
17 24 small prisms	0.014	215	9	8	0.28	4 098	0.04097±20	0.2925±18	0.05177±18	258.9	260.5	275.5
MAL1 – Malanaggio diorite, dioritic facies, Perosa Argentina												
18 5 big prisms	0.043	650	29	8	0.30	34 930	0.04575±22	0.3288±18	0.05212±8	288.4	288.6	290.9
19 2 biggest prisms	0.033	461	21	8	0.29	6 590	0.04599±22	0.3305±18	0.05211±10	289.9	289.9	290.4
20 8 short prisms	0.048	612	28	9	0.31	13 446	0.04595±22	0.3303±18	0.05213±8	289.6	289.8	291.2
MAL2 – Malanaggio diorite, granodioritic facies, Albarea												
21 17 short prisms	0.043	212	10	8	0.29	20 872	0.04568±22	0.3283±18	0.05212±8	288.0	288.2	290.5
22 11 needles	0.005	569	23	9	0.31	5 503	0.04032±18	0.2891±16	0.05201±12	254.8	257.9	285.8
23 3 big prisms + bubbles	0.048	189	9	8	0.29	11 539	0.04567±24	0.3278±18	0.05206±10	287.9	287.9	288.0

*: radiogenic; a: in mole-% relative to total radiogenic Pb; b: calculated on the basis of ^{208}Pb/^{206}Pb ratios, assuming concordancy; c: corrected for spike Pb and for fractionation; d: corrected for fractionation, spike, U and Pb blanks, and initial common Pb (STACEY and KRAMERS, 1975) when present (+), error estimates (95% confidence level) refer to the last significant digits of the isotopic ratios and reflect reproducibility of standards, measurement errors and uncertainties in the common Pb correction.

and display rather large analytical uncertainties. More work is clearly needed, but age boundaries can be set using the procedure applied to sample SAN. (14) is similar to fraction (9) of SAN and is concordant within its large error ellipse at U–Pb ages of 269.1 ± 1.2 and 269.6 ± 1.8 Ma, respectively (1.7% discordancy). (14) thus sets the lower bound of the possible range for the crystallization time of the Freidour granite. Considering that fractions (15) and (17) are collinear with (14) and most probably experienced lead loss during the Alpine orogeny, the calculation procedure used for sample SAN is applied and yields a projected age of 276 ± 7 Ma for a probability of fit of 58%. Consequently, we propose a preliminary age range of 268 to 283 Ma for the crystallization time of the Freidour granite.

It is worth noting that samples SAN and FRE, which are very similar in all respects, yielded almost identical crystallization age ranges, and that fractions (14) of FRE and (9) of SAN plot comformably within error of each other. This suggests that the true crystallization age of both granites is about the same and closer to 270 than 280 Ma.

THE MALANAGGIO DIORITE (AUCT.)(MAL1+2)

Both samples yielded clear, mostly colourless to pale pink, euhedral zircons, representing a wide variety of S sub-types (Figs 4, 6 d, e). Very elongated prisms (l/w >> 2) characterise MAL1. Zoning and overgrowths are developed in the low-T index (PUPIN, 1980) sub-types. Inclusions are as usual, but channel-like cavities are rare. Pyramidal and, to a lesser extend, prismatic faces of some crystals display pitted surfaces (Fig. 6e). The origin of such a rough aspect is unclear, it might be of metamorphic (resorption) origin, or related to the metamictisation of U-rich overgrowths.

Three fractions (18–20, Tab. 3) were selected from the dioritic sample MAL1. They are rather rich in uranium (461–650 ppm), analytically concordant and overlap within error (Fig. 7e). (19) and (20) are superimposed at an U–Pb age of 290 ± 2 Ma, which is interpreted as the crystallization time of the dioritic magma.

From the granodioritic sample MAL2 were also selected three multi-grain fractions (21–23, Tab. 3, Fig. 7f). (23) is on the Concordia curve at 287.9 ± 1.4 Ma, an age corroborated by the concordant 288.1 ± 1.4 Ma of (21). On the other hand, the fragile needles of (22) record a substantial lead loss, only partly eliminated by a light, non-destructive, abrasion process. This fraction, together with (21) and (23), defines a discordia line with a geologically meaningful lower intercept at 32 ± 46 Ma. The concordant U–Pb age of 288 ± 2 Ma is proposed for the crystallization of the granodioritic facies of the Malanaggio diorite (auct.).

MAL1 and MAL2 are contemporaneous within errors, and it is objectively not possible to establish if and how long the dioritic facies of the intrusion predated the granodioritic one from a geochronological point of view.

Discussion

As shown in many case studies, the U–Pb method of dating on zircon is well suited to obtain crystallization ages of highly (poly-)metamorphosed igneous rocks. All analyzed samples yielded at least one concordant zircon fraction within analytical errors, which means that potential effects of post-magmatic disturbing events can be overcome by a systematic selection of the best flawless and core-free zircons from the least deformed rock samples, followed by an extensive abrasion procedure. Zircon can survive amphibolite-facies metamorphism, as long as no partial melting occurs in the rock. In the same way, no significant effect can be objectively ascribed to the eo-Alpine high-pressure metamorphic event, but it is not clear to which extend the northern Dora-Maira ever experienced very high pressure conditions. Our unpublished data on eclogitized metagranites in the Alps point to the same conclusion (e.g. Mt-Mucrone metagranite, Sesia-Lanzo zone, Southern Italian Alps, eclogitized under minimum conditions of 1.4 GPa and 600 °C, OBERHÄNSLI et al., 1985): zircon survived the high-pressure overprint, as abraded crystals still yield perfectly concordant magmatic ages. Generally speaking, our experience in dating metagranitoids shows that zircon is less sensitive to high lithostatic pressure than to high temperature overprints.

As expected from field work, most of the dated metagranites were emplaced during Late Paleozoic times, i.e. in relation with the Variscan orogeny s.l. On the other hand, the 457 ± 2 Ma old polymetamorphic augengneiss of Punta Muret probably belongs to a large Caledonian tectonomagmatic province, documented in many parts of the pre-Mesozoic basement of the Alpine realm (HEINISCH and SCHMIDT, 1982). Evidence for this major magmatic event are the so-called "younger orthogneisses" of Ordovician to Silurian age, dated in particular in the external crystalline massifs (Mont-Blanc augengneiss at 453 ± 3 Ma, BUSSY and VON RAUMER, 1993; Aar Innertkirchen migmatite at 445 ± 2 Ma, SCHALTEGGER, 1993; Gotthard Streifengneiss at 438 +5/–8 Ma, SERGEEV and STEIGER, 1995); in Penninic units (Verzasca gneiss at 445 ± 5 Ma, STEIGER et al., 1994; Berisal gneiss[?], KÖPPEL et al., 1980); in the upper Austroalpine Silvretta nappe (Flüela granitic association around 450 Ma, Rb/Sr data reported in MÜLLER et al., 1994; concordant U–Pb zircon data in LIEBETRAU et al., 1994) or in the Eastern Alps (monzonitic Oetztal gneiss at 455 +2/–4 Ma, SÖLLNER and HANSEN, 1987). Among these intrusions, some display calc-alkaline, metaluminous characteristics (e.g. in the Mont-Blanc), others peraluminous ones (e.g. in the Silvretta), both types being commonly associated in space and time in orogenic belts. In terms of paleogeography, the 457 Ma age of the Punta Muret augengneiss suggests that during Ordovician times, existing parts of the future Dora-Maira massif belonged to the same continental block as the above-mentioned units, i.e. Gondwana.

The Variscan belt in Europe is characterized by a huge late- to post-orogenic magmatic activity, tightly linked to an extensional tectonic regime (SCHALTEGGER and CORFU, 1995; SCHALTEGGER, 1995). Available U–Pb data in the Central Alps and adjacent areas point to an age gradient along a NW–SE transect, with older values in the external (i.e. NW) units of the belt and younger ones in more internal units (Penninic and Austroalpine domains, southern Alps). According to SCHALTEGGER and CORFU (1995) and SCHALTEGGER (1996), magmatic activity is linked to short-lived tectonic episodes, separated by periods of apparent quiescence. A first magmatic episode documented at c. 330–345 Ma is apparently restricted to the northern side of the Helvetic-Penninic boundary; the oldest ages being recorded in the extra-Alpine southern Vosges by volcanic deposits between 345 and 340 Ma (SCHALTEGGER, 1995). Most of the granites related to this event show a pronounced magnesian and/or potassic character (DEBON et al., 1994; SCHALTEGGER and CORFU, 1995), such as the Vosgian Ballons and Crêtes granites (340–341 Ma, SCHALTEGGER, 1995), and intrusions in some of the so-called external crystalline massifs of the Alps: Sept-Laux granite, Belledonne massif (332 Ma, DEBON et al., 1994); Tödi granite (333 Ma, SCHALTEGGER and CORFU, 1995) and ultrapotassic rocks of the Val Punteglias (334 Ma, SCHALTEGGER and CORFU, 1992), both located in the Aar massif.

A second episode started at c. 310 Ma and yielded many intrusions of calc-alkaline or peraluminous type. The magmatic activity apparently shifted towards the inner parts of the belt, as no upper Carboniferous ages are recorded in the Vosges and Black Forest massifs (SCHALTEGGER, 1995). The latter lasted from 310 to 298 Ma in the Aar (SCHALTEGGER, 1994), 307 to 304 Ma in the Mont-Blanc (BUSSY and VON RAUMER, 1993) and 301 to 295 Ma in the Gotthard massif (GUERROT and STEIGER, 1991; SERGEEV and STEIGER, 1995). To our knowledge, more internal units (considering a pre-Alpine, Permo-Triassic paleogeography) only contain granitic rocks younger than 295 Ma (see HUNZIKER et al., 1992 for a general review), down to 270 Ma in the Penninic basement (Randa orthogneiss, BUSSY et al., 1996) and 262 Ma in the southern Alps (Lugano calc-alkaline volcanics, Rb/Sr data, STILLE and BULETTI, 1987). On the whole, there is a progressive evolution towards more alkaline melts with time, ending with true Permo-Triassic alkaline to peralkaline massifs emplaced along large-scale continental fractures (BONIN, 1988).

The magmatic activity in the northern Dora-Maira started at around 304 Ma (Cavour leucogranite); unsampled minor intrusions might be slightly older. This starting point is also documented by the 301 ± 1 Ma age obtained by Paquette for the Brossasco granodiorite (see introduction). The latter intrusion is of calc-alkaline type, as the Cavour leucogranite probably is. These granites are followed at 290 Ma by the calc-alkaline diorite-granodiorite Malanaggio series and, subsequently, by the more alkaline Sangone and Freidour granites between 280 and 270 Ma. Although not pronounced, this shift towards alkaline melts is in keeping with the general evolution of the Variscan magmatism in Europe (BONIN, 1988).

From a geographic point of view, the internal age distribution of plutons within the Dora Maira massif does not fit the overall NW–SE Variscan age gradient mentioned above. This is not surprising as the original relative emplacements of the intrusions have changed during Tertiary nappe tectonics. But considering the position of the (future) Dora-Maira massif as a whole within the Variscan belt, the observed age and chemical ranges are in agreement with the expected trend: no pre-Westphalian intrusions, no Mg–K magmas, true calc-alkaline melts as young as 290 Ma, Permian magmatic activity of alkaline affinity.

It has been shown for some years that the Variscan magmatism occurred simultaneously with a late orogenic extensive – locally transtensive or transpressive – tectonic regime, a context which has been compared to the Basin and Range province of western USA (SCHALTEGGER and CORFU, 1995 and references therein). On the other hand, the fundamental mechanisms which initiated such a large-scale crustal extension are not yet well understood. The post-orogenic gravitational collapse of a thickened crust is certainly a possible mechanism (e.g. BURG et al., 1994, SCHALTEGGER and CORFU, 1995), but it might not be applicable to the Variscan context, mainly for a question of size of the orogen and amplitude of uplift (STAMPFLI, 1996). According to STAMPFLI (1996), the European Variscan belt was an active Andean-type continental margin during lower Carboniferous times, the Paleotethys oceanic crust being subducted northwards under the southern margin of the European continent. A "Basin and Range" situation would develop as a back-arc opening within the orogenic belt in response to the subduction of the Paleotethys mid-ocean ridge. In such a distensive environment, the observed shift with time of the Late-Variscan magmatic activity towards the south could be related to a propagating gravitational collapse triggered by the roll-over effect of the retreating sinking Paleotethyan slab (STAMPFLI, 1996).

Additional high-precision dating and geochemical characterization of magmatic rocks are clearly needed to further test the apparent correlation of both age and chemistry of granitic intrusions with their respective geographic position within the Variscan belt. Key regions would be highly metamorphic internal Alpine units (Lower Penninic nappes), whose pre-Alpine paleogeographic position was in between external (Vosges, Black Forest, Aar, Mont-Blanc...) and internal (Dora-Maira, Monte Rosa, Gran Paradiso...) zones. Additional data are also necessary to check if the magmatic activity is a series of discrete short-lived episodes all over the orogenic belt, or only in its northern parts (e.g. SCHALTEGGER, 1996). Answering these questions will help solving the more general problem of the geodynamic evolution of the Variscan orogeny: i.e. was it an active continental margin with a rather continuous magmatic activity and a chronological-chemical trend at the cordillera scale, or the result of the gravitational collapse of a thickened crust coupled to discrete tectono-magmatic events?

Conclusions

The following conclusions can be drawn from the chemical and isotopic data presented in this study: (1) the U–Pb method of dating on zircon is well suited to obtain the magmatic crystallization age of highly (poly-)metamorphic metagranites. (2) the 457 ± 2 Ma old Punta Muret peraluminous augengneiss (PAG) records a mid-Ordovician magmatic activity in the Dora-Maira massif; it belongs to the widespread group of Caledonian orthogneisses identified in most pre-Mesozoic units of the Alps. This supports a Gondwanian origin for the Dora-Maira massif at this time. (3) all other dated granitoids are of Upper Carboniferous age and relate to the Late-Variscan orogeny. (4) the data obtained are in agreement with the overall age distribution observed across the Variscan belt, the latter displaying decreasing values from the Vosges to the southern Alps. (5) the chronological evolution from calc-alkaline (and peraluminous?) to more alkaline magmas in the Dora-Maira massif is similar, although less pronounced, to that observed at a larger scale during the Late- to Post-Variscan magmatic cycle in Europe.

In a first approximation, the age distribution of the granitic rocks across the Variscan belt reflects a migration of the magmatic activity towards the internal parts of the orogen. A possible scenario could be a Carboniferous back-arc, distensive Basin and Range situation, propagating southwards in response to the roll-back of a still subducting Paleotethyan oceanic plate along an active continental margin.

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