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Geochronology and Sr isotope geochemistry of late-Hercynian dykes from Sardinia

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Abstract

Fifteen Rb/Sr and $^{40}Ar/^{39}Ar$ mineral ages were obtained on peraluminous, calcalkaline, transitional and alkaline late-Hercynian dykes intruding the Hercynian batholith in Northern and Central Sardinia.

Ages and initial Sr isotopic ratios (Sr_i) closely mirror the subdivision into petrochemical groups and outline two tectonic domains with a different magmatic history.

In the South, dyke intrusions are limited to peraluminous and high Sr_i calcalkaline products clustered between 298 ± 5 and 289 ± 4 Ma with Sr_i between .7164 and .7091.

In the North, which underwent a significant exhumation and crustal thinning, the evolution took place from peraluminous (282 ± 4 to 268 ± 4 Ma, .7100 to .7149) to low Sr_i calcalkaline (270 ± 10 Ma, ca. .7060) to alkaline dykes (230 ± 10 Ma, ca. .7040). The tectonic environment, thus, changed from orogenic to anorogenic continental.

Keywords: Sardinia, dykes, Hercynian orogen, Rb/Sr dating, $^{40}Ar/^{39}Ar$ dating.

1. Introduction

On the island of Sardinia, Hercynian magmatic products are exposed over about 10,000 km^2. It is a portion of the Hercynian chain that has been unaffected by Alpine orogenetic events and thus offers an excellent opportunity to study the Permo-Carboniferous events with only minor subsequent overprints.

Among the Permo-Carboniferous magmatic products, special attention must be given to the dyke swarms; although volumetrically minor they densely intrude most of the Sardinian basement along preferred directions (Vaccaro, 1990). Dykes have been grouped into a large variety of petrochemical families (Atzori and Traversa, 1986), which can be related to the last phases of the tectono-magmatic evolution of the Hercynian chain. Thus, this evolution can be temporally constrained by dating the typical dykes associated with each tectonic phase.

The geographical distribution of the dyke populations is far from uniform. In the southern-central sector almost only calc-alkaline and subalkaline dykes are found, except for a few peraluminous ones near the edge of the central-western part of the batholith. On the contrary, transitional and calc-alkaline dykes predominate in the northern sector, with sporadical occurrences of alkaline ones, restricted to the immediate proximity of shear zone.

In those parts of the batholith that underwent a limited uplift, i.e. the south, transitional dykes are absent, while in the north, where uplift has exposed deeper structural levels, the setting became more and more continental, and consequently the magmatic products derived from deeper and deeper recharge areas.

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This paper presents 10 Rb/Sr and 6 ^{40}Ar/^{39}Ar mineral ages on peraluminous, calc-alkaline and alkaline dykes. We also present Sr isotopic data on compositionally similar dykes which were not directly dated but which may be considered coeval basing on field evidence and structural analogies. Another group, transitional dykes, is seen from field relationships to be contemporaneous to the alkaline ones (VACCARO, 1990). WR Sr isotopic data of the one analysed sample are presented with an age-correction appropriate for the age of the alkaline group.

The analyzed samples were collected in various parts of the Sardinian batholith (Fig.1). Exact locations, petrography and major and trace element geochemistry are given by ATZORI and TRAVERSA (1986) and VACCARO (1990); they are summarized in the Appendix.

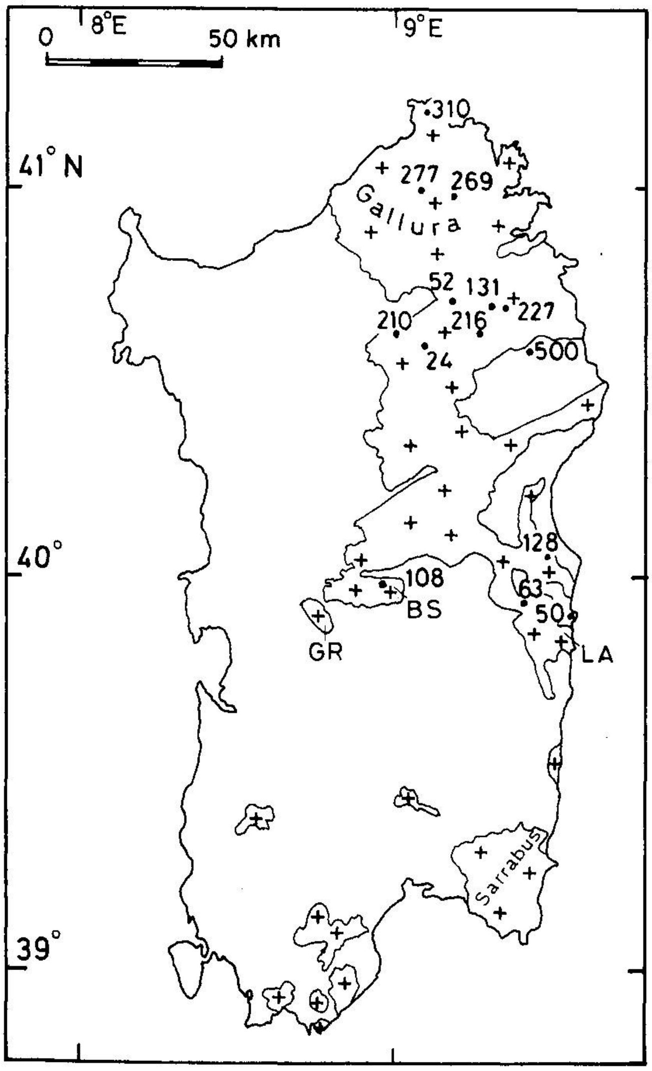

Fig. 1 Geological sketch map of Sardinia. Crosses, Hercynian batholith; dots, sample location. Massifs are indicated as follows: LA, Lanusei; BS, Busachi-Sorgono; GR, Monte Grìghini.

All samples have non-foliated texture; they therefore postdate the last deformation phases, which are thought to be coeval with the uplift of the mountain belt (OGGIANO and DI PISA, 1988).

2. Analytical techniques

Rb and Sr contents were determined (except Rb for B216 whole-rock) by isotopic dilution procedure using ^{87}Rb (98%) and ^{84}Sr (99.89%) spikes, respectively.

Whole-rock powders and biotite separates were dissolved by a HF + $HClO_4$ mixture. The biotite solutions were split for separate measurements of Rb content, and of Sr content and isotopic composition; on the contrary, whole-rock solutions were spiked for both Rb and Sr, from the beginning. The resulting uncertainty on the ^{85}Rb/^{87}Sr ratio is 1.5%, as determined from reproducibility tests.

Isotopic analyses were carried out by a TH5 Varian MAT single collector mass-spectrometer. Repeated analyses of NBS §§ 987 Sr standard gave an external reproducibility of 5×10^{-5} with an average value of .71028 (n = 23). Ages were calculated by using $\lambda_{87Rb} = 1.42 \times 10^{-11} a^{-1}$.

Ar analyses and data reduction followed VILLA (1991, this volume). Data are presented in tables 1 and 2.

3. Results

We analyzed 14 whole-rock samples as well as 9 micas by Rb/Sr, and 4 hornblendes, 1 muscovite and 1 potassium-feldspar by ^{40}Ar/^{39}Ar (Tab. 1, 2). The samples represent several of ATZORI and TRAVERSA's (1986) petrochemical groups; we shall present the results for each group individually and then discuss the general picture.

3.1. PERALUMINOUS SUITE

Dyke B 108 cuts the Busachi-Sorgono granodiorite (Central Sardinia), whose biotite Rb/Sr ages are 284–287 Ma (DEL MORO et al., 1990). The muscovite yields concordant Rb/Sr (298 ± 5 Ma) and Ar/Ar plateau (295) and isochron (294) ages and is near to the composite (peraluminous and calc-alkaline typologies) Grighini mylonitic granite (303 ± 18 Ma on WR and 299–295 on 5 muscovites for the peraluminous portion, CARMIGNANI et al., 1987, DEL MORO et al., 1990; and 294–295

Tab. 1 Rb/Sr analytical results.

Sample	Material	Massif or region	Rb	Sr	$^{87}Rb/^{86}Sr$ ± 1.5%	$^{87}Sr/^{86}Sr$ ± 2 σ	Age (Ma) ± 2 σ	$(^{87}Sr/^{86}Sr)_i$ ± 2 σ
Peraluminous Suite								
B108	WR	Sorgono	192	54	10.3	.76015 ± 17		
	ms		719	9.1	254	1.7949 ± 32	298 ± 9	.7165 ± 19
B128	WR	Baronie	180	169	3.08	.72391 ± 25		
	bi		380	8.7	133	1.2632 ± 6	291 ± 9	.7111 ± 6
B269	WR	Gallura	207	76	7.87	.74483 ± 62		
	bi		588	7.8	238	1.6212 ± 4	268 ± 8	.7149 ± 14
Sc24°	WR	M. Lerno	971	7.9	411	2.3386 ± 11		
	ms		1958	4.4	2565	10.9479 ± 43	281 ± 10	.6976 ± 813
Sc52	WR	Concas	282	17.7	47.0	.89596 ± 42		
	bi		1597	11.1	494	2.6324 ± 13	273 ± 9	.7137 ± 88
	ms		1271	7.1	650	3.3172 ± 26	282 ± 9	.7073 ± 85
Sc131	WR	Concas	205	38.3	15.6	.77254 ± 21		
	bi		1298	6.2	794	3.8787 ± 23	280 ± 9	.7103 ± 28
	ms		850	6.8	420	2.3949 ± 12	282 ± 9	.7099 ± 27
Calc-alkaline suite								
B50	WR	Ogliastra	85	347	.708	.71203 ± 7		.7091*
B63	WR	Ogliastra	279	279	2.90	.72244 ± 7		
	bi		388	12.8	91.0	1.0843 ± 4	289 ± 9	.7105 ± 9
B210	WR	Goceano	128	205	1.81	.71719 ± 27		.7097*/.7102†
B277	WR	Gallura	76	527	.418	.70827 ± 4		.7067†
B310	WR	Gallurai	77	464	.482	.70777 ± 11		.7059†
Alkaline suite								
B216	WR	Concas	17°°	1120	.043	.70466 ± 3		.7045**
B500	WR	Baronie	58	1200	.139	.70428 ± 5		
	bi + ap		198	387	1.50	.70836 ± 26	210 ± 15	.7039 ± 1
Transitional basalt								
B227	WR	Concas	40	278	.417	.70659 ± 12		.7052**

° pegmatite vein
°° by XRF method, after ATZORI and TRAVERSA (1986)
* assuming an age of 290 Ma
** assuming an age of 230 Ma
† assuming an age of 270 Ma

Ma on 2 biotites for the calcalkaline one; DEL MORO et al., 1990). What is clear in any case is the tight chronological correlation between dyke B108 and the large Grighini granite. There is a similarity in the initial Sr isotopic ratio, too: .7164 ± 10 for the dyke against .7135 ± 24 for the peraluminous granite. Both may in fact derive from partial melting of the same source material, the pelitic sediments, whose age-corrected isotopic composition ranges between .7150 and .7195 for the northern part of the basement (SQUANDRONE, 1989).

The K-feldspar coexistent with the muscovite has yielded a disturbed Ar–Ar spectrum, with step ages varying between 203 and 220 Ma (Fig. 2). This age discrepancy could be explained either by very slow cooling (3–4°/Ma) or by a later mild thermal event. An argument against the former is the concordance of the K/Ar and Rb/Sr muscovite age on B108, since Rb/Sr as a rule gives older cooling ages than K/Ar; this indicates a fairly fast cooling, as does the proximity of biotite and muscovite Rb/Sr ages in the Mt. Grìghini granite. An argument for the latter are the rejuvenated biotite

Tab. 2 Stepwise heating data; all isotopes in pl/gr, errors are 1σ

B 277 hb .0975 g J = 0.003251

T (°C)	$^{40}Ar_{tot}$	^{39}Ar	^{38}Ar	^{37}Ar	^{36}Ar	t (Ma)
800	429.4 ± .9	7.397 ± 24	.346 ± 12	8.6 ± .2	.8110 ± 81	145.1 ± 1.8
950	357.3 ± .1	9.403 ± 15	.219 ± 3	26.9 ± .5	.1219 ± 13	191.5 ± .4
1000	199.7 ± .1	4.736 ± 10	.217 ± 2	29.0 ± .4	.0743 ± 8	211.0 ± .5
1050	446.4 ± .2	9.549 ± 18	.489 ± 4	85.6 ± .6	.1064 ± 16	243.4 ± .5
1080	761.0 ± .5	15.296 ± 17	.788 ± 4	157.6 ± .7	.1310 ± 8	263.5 ± .3
1100	1080.5 ± .4	21.276 ± 30	1.098 ± 5	231.4 ± 1.3	.1600 ± 13	270.6 ± .4
1130	491.4 ± .3	9.866 ± 18	.529 ± 4	102.9 ± .7	.1093 ± 7	260.0 ± .5
1160	847.3 ± .2	16.633 ± 26	.902 ± 5	181.6 ± .8	.1491 ± 15	269.3 ± .4
1200	403.4 ± .2	7.626 ± 17	.425 ± 2	84.8 ± .8	.1029 ± 9	272.6 ± .6
1500	235.9 ± .1	3.433 ± 8	.220 ± 3	37.6 ± .5	.2424 ± 19	267.2 ± 1.0
						t_{tot}= 246.3

B 108 ms 0.0075 g J = 0.003184

T (°C)	$^{40}Ar_{tot}$	^{39}Ar	^{38}Ar	^{37}Ar	^{36}Ar	t (Ma)
700	6093.5 ± 6.2	94.85 ± .22	1.976 ± 32	1.99 ±3.02	3.7249 ± 327	279.6 ± .8
750	3242.7 ± 2.4	56.09 ± .12	0.760 ± 22	0 ±3	0.4343 ± 119	293.7 ± .7
800	6227.7 ± 6.3	107.92 ± .22	1.447 ± 30	5.31 ±2.85	0.7110 ± 159	294.9 ± .7
850	14613.9 ± 14.8	253.70 ± .36	3.322 ± 38	6.17 ±2.20	1.3394 ± 254	296.2 ± .5
900	17315.2 ± 17.8	302.48 ± .37	3.949 ± 44	2.55 ±2.29	1.2470 ± 142	296.1 ± .4
930	12863.3 ± 14.4	225.58 ± .46	2.919 ± 28	0.13 ±3.02	.7546 ± 173	296.1 ± .6
960	7787.3 ± 7.8	136.43 ± .23	1.809 ± 35	6.04 ±3.28	.6635 ± 189	294.3 ± .6
1000	7623.3 ± 7.8	132.19 ± .24	1.881 ± 58	-.78 ±4.02	.8485 ± 209	294.9 ± .6
1100	14098.7 ± 15.7	246.77 ± .39	3.406 ± 40	4.75 ±3.45	1.1942 ± 154	294.6 ± .5
1300	11287.0 ± 10.0	200.23 ± .34	2.635 ± 35	1.90 ±3.07	0.6150 ± 160	293.4 ± .5
1700	1687.2 ± .8	25.51 ± 9	0.576 ± 17	-1.55 ± 3.63	1.1695 ± 93	279.2 ± 1.1
						t_{tot}= 294.1

B 108 Kf .0120 g J = .003184

T (°C)	$^{40}Ar_{tot}$	^{39}Ar	^{38}Ar	^{37}Ar	^{36}Ar	t (Ma)
700	8230.8 ± 8.4	158.25 ± .22	3.337 ± 26	3.53 ±2.85	3.6476 ± 274	242.6 ± .5
800	3607.3 ± 3.2	90.26 ± .13	1.373 ± 25	-0.36 ±1.45	.4786 ± 87	208.1 ± .4
850	3862.6 ± 2.9	98.06 ± .15	1.501 ± 19	3.11 ±1.9	.5893 ± 127	204.0 ± .4
900	4712.6 ± 5.2	118.79 ± .17	1.832 ± 23	4.67 ±1.40	.7145 ± 72	205.5 ± .4
930	1772.5 ± 1.9	44.95 ± .10	.697 ± 19	-0.16 ±1.84	.3169 ± 71	202.7 ± .5
960	4602.4 ± 4.4	114.12 ± .13	1.799 ± 19	-0.54 ±2.08	.8362 ± 112	206.9 ± .3
1000	4772.2 ± 5.2	114.71 ± .22	1.813 ± 20	0.93 ±3.29	.9123 ± 82	212.5 ± .4
1030	4271.9 ± 3.7	101.06 ± .16	1.637 ± 17	5.34 ±1.69	.8062 ± 111	215.9 ± .4
1060	9122.5 ± 10.6	214.43 ± .35	3.450 ± 31	2.10 ±1.43	1.5455 ± 202	218.4 ± .4
1100	4969.2 ± 5.3	116.23 ± .18	1.810 ± 14	3.03 ±2.31	.7985 ± 125	220.0 ± .4
1130	5186.5 ± 4.8	121.96 ± .24	1.914 ± 30	0 ±3	.7527 ± 114	219.9 ± .5
1180	7108.7 ± 7.5	164.75 ± .22	2.607 ± 17	0 ±3	1.0442 ± 238	222.8 ± .4
1300	561.8 ± .4	11.43 ± 3	0.256 ± 13	2.88 ±2.26	.2492 ± 89	230.1 ± 1.3
1700	68.02 ± .11	0.559 ± 17	0.052 ± 14	3.22 ±2.18	.1385 ± 89	262.0 ±24.4
						t_{tot}= 217.2

B 63 hb .0907 g J = 0.00386

T (°C)	$^{40}Ar_{tot}$	^{39}Ar	^{38}Ar	^{37}Ar	^{36}Ar	t (Ma)
700	1378.8 ± .6	4.392 ± 13	1.118 ± 17	10.4 ± .2	3.8872 ± 183	289.4 ± 6.3
800	364.4 ± .3	6.015 ± 15	0.201 ± 3	7.3 ±.2	0.2703 ± 24	259.5 ± .9
950	622.2 ± .4	11.416 ± 17	0.679 ± 4	23.6 ± .3	0.3547 ± 23	249.8 ± .5
1000	3698.2 ± 4.0	67.216 ± 82	20.348 ± 46	478.2 ± 2.2	0.5718 ± 31	289.2 ± .4
1050	1044.9 ± .6	19.314 ± 28	5.796 ± 14	132.5 ± 1.1	0.1608 ± 18	284.7 ± .4
1080	182.0 ± .1	3.072 ± 6	0.657 ± 4	17.2 ± .4	0.1125 ± 8	267.7 ± .7
1100	282.3 ± .2	4.890 ± 12	1.426 ± 5	38.1 ± .4	0.1195 ± 11	279.5 ± .7
1130	616.3 ± .3	10.806 ± 18	3.727 ± 10	93.3 ±1.0	0.2124 ± 25	283.6 ± .5
1160	784.0 ± .7	13.900 ± 25	4.493 ± 13	107.9 ± 1.2	0.2490 ± 29	282.5 ± .6
1250	97.3 ± .1	1.527 ± 5	0.510 ± 4	12.9 ± .2	0.660 ± 13	282.1 ± 28
1600	124.6 ± .1	0.871 ± 2	0.301 ± 4	7.3 ±.2	0.2782 ± 30	270.5 ± 5.2
						t_{tot}= 281.0

B 310 hb .0312 g J = 0.003254

T (°C)	$^{40}Ar_{tot}$	^{39}Ar	^{38}Ar	^{37}Ar	^{36}Ar	t (Ma)
800	702.3 ± 2.3	8.325 ±.142	0.899 ± 68	14.9 ±1.2	1.5425 ± 378	166.9 ± 7.7
1000	599.5 ± .4	13.698 ± 27	0.974 ± 12	66.3 ±1.1	0.4239 ± 29	195.2 ± .5
1050	973.4 ± .2	18.542 ± 31	1.314 ± 10	166.8 ± 1.3	0.3401 ± 35	262.3 ± .5
1100	2176.3 ± 1.9	41.580 ± 67	2.752 ± 11	386.9 ± 2.5	0.4873 ± 74	271.6 ± .5
1130	526.2 ± .2	9.716 ± 28	0.627 ± 7	90.9 ± .9	0.1951 ± 27	268.3 ± .8
1160	155.5 ± .1	2.615 ± 8	0.184 ± 9	25.2 ± .7	0.1008 ± 26	267.8 ± 1.6
1200	684.2 ± .6	12.159 ± 20	0.808 ± 10	121.9 ± .9	0.2889 ± 38	273.9 ± .6
1500	608.3 ± .3	8.781 ± 26	0.632 ± 7	79.3 ±4.2	0.6631 ± .96	261.7 ± 1.0
1600	824.3 ± .4	0.843 ± 11	0.515 ± 6	3.5 ±.4	2.7056 ± 212	167.0 ±40.0

t_{tot} = 251.0

B 500 hb 0.0664 g J = 0.003267

T (°C)	$^{40}Ar_{tot}$	^{39}Ar	^{38}Ar	^{37}Ar	^{36}Ar	t (Ma)
660	1196.5 ± 1.5	4.534 ± 14	0.801 ± 9	15.16 ± .23	3.4699 ± 157	211.7 ± 5.4
770	1846.0 ± 2.2	13.002 ± 28	1.193 ± 10	39.00 ± .33	4.4116 ± 177	232.2 ± 2.2
880	304.3 ± .3	5.366 ± 14	0.137 ± 4	3.87 ±.11	0.2973 ± 31	223.7 ± 1.1
950	385.5 ± .2	7.207 ± 17	0.208 ± 3	4.90 ±.10	0.3497 ± 28	217.5 ± .8
1000	310.7 ± .2	6.705 ± 14	0.199 ± 3	5.37 ±.14	0.1974 ± 20	209.7 ± .6
1250	12727 ± 127	288.568 ± .385	--- ---	768.8 ± 2.2	1.1792 ± 64	238.1 ± 2.3
1500	1195.5 ± .7	21.157 ± 39	1.981 ± 13	96.80 ± .48	1.1229 ± 82	228.4 ± .7

t_{tot} = 235.8

ages (160–220 Ma) obtained by DEL MORO et al. (1990) on basement rocks, E of Mt. Grighini. In this light, we can interpret the Busachi-Sorgono biotite ages as an evidence of the partial opening of the Rb/Sr system.

More samples from different areas were dated by Rb/Sr. The biotite from a porphyric dyke, B 128 (which intrudes a coarse-grained «G II» monzogranitic granodiorite, as defined by

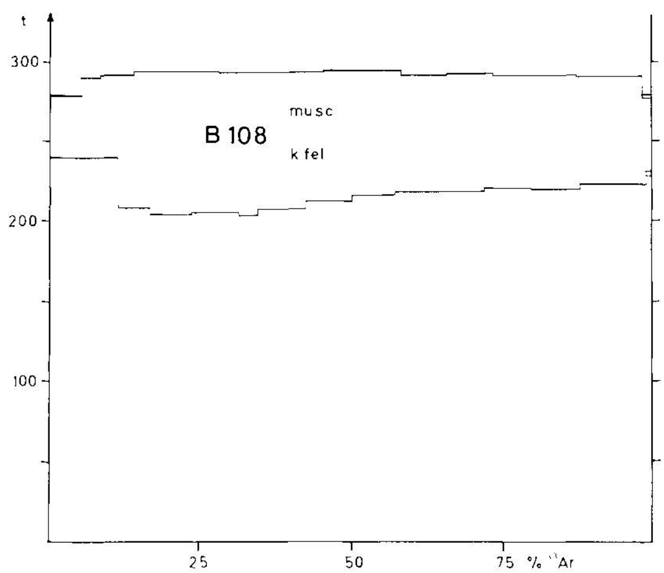

Fig. 2 Age spectra for coexisting muscovite and K-feldspar of dyke B 108. Width of error boxes, or thickness of lines, represents 1 σ error.

ORSINI, 1980) gives 292 ± 4 Ma, Sr_i = .7111 ± 3. The biotite from a fine-grained dyke, B 269 (which intrudes the pink inequigranular monzogranite in Gallura) gives 268 ± 4 Ma, Sr_i = .7149 ± 9. The two ages seem to show that different regions underwent similar magmatic episodes at different times. The Galluran dyke B 269 is significantly younger than the Rb/Sr mica ages of the surrounding granites, about 290 Ma (DEL MORO et al., 1975, recalculated with $\lambda^{87}Rb = 1.42 \times 10^{-11}a^{-1}$). This could reflect either a later emplacement or a subsequent disturbance. Its initial Sr isotopic composition is typical of partial melts deriving from high Rb/Sr sources (possibly pelites or sandstones) while the other peraluminous dyke, B 128, requires a much less radiogenic protolith.

Two complementary samples from the peraluminous Concas leucogranite were analyzed: Sc 52 represents the deformed border facies and Sc 131 the undeformed interior. The two muscovite Rb/Sr ages are concordant and average 282 Ma (Tab. 1); the biotite ages are likewise concordant around 277 Ma. This allows us to reconstruct the following picture: the granite was emplaced while shear was taking place, and its borders only are foliated; the deformation was not penetrative but localized in a narrow band, as is typical for shear deformation. The comparatively small stock then cooled homogeneously, producing no age zonation between core and border. Isotopic closure was achieved after the deformation had ended.

The muscovite from pegmatite Sc 24 has a 281 ± 5 Ma Rb/Sr age. Among these latter 3 samples, the initial Sr isotope ratio with lowest uncertainty is that of Sc 131, .7100 ± 14; this is the lowest value in the peraluminous typology, and suggests a link with the calc-alkaline suite (see next §).

3.2. CALC-ALKALINE SUITE

Three dykes were dated by Ar/Ar on amphibole: B 277 and B 310 from the N and B 63 from the S of the batholith; the latter also by Rb/Sr on biotite.

A remark on the hornblende spectra of the present study must be made at this point. In all four hornblendes shown in table 2, step ages are approximately constant, within 5–10 Ma, during the gas release. Yet they fail the usual criterion for plateaus (e.g. DALRYMPLE and LANPHERE, 1974), because the difference between successive steps exceeds the 2 sigma error (usually 1–2 Ma). That is to say, the analytical precision is better than the geochemical perturbations affecting the Ar released in the different steps. Firstly, we must note that this behaviour is peculiar to the Sardinian hornblendes as other samples irradiated together and analyzed during the same period show regular trends. Secondly, we can relate the age-hopping to irregularities in the Ca/K spectrum as well. It is therefore tempting to ascribe these features to a complex microstructure of our amphiboles, which might in turn result from the emplacement mechanism and subsolidus evolution of the calc-alkaline dykes.

As for the age assignment of these irregular spectra, we note that fitting an isochron results in scatter exceeding the analytical error (i.e. MSWD >> 1). The calculated uncertainty on the isochron age contains a term which accounts for this high dispersion; therefore, the uncertainty on isochron ages is much higher than the typical uncertainty on individual steps (Tab. 2), and will be used as a realistic estimate in the following discussion.

The sample from Ogliastra, B 63, has a Rb/Sr biotite age of 289 ± 4 Ma, indistinguishable from the nearby peraluminous dyke B 128 (see above). The Ar–Ar age (285.8 ± 7.2 Ma) coincides with the Rb/Sr age.

As was the case for the peraluminous dykes, the proximity of cooling ages given by different geochronometers argues for a fast cooling, so that the ages we obtain are very close to the actual emplacement.

In summary, the magmatic evolution of the sector south of 40°10' N is rather compressed. The first products are tonalitic-granodioritic stocks such as Busachi-Sorgono (> 298 Ma) and Lanusei (302 Ma; recalculated after DEL MORO et al., 1975, with $\lambda^{87}Rb = 1.4210^{-11}/a$). Monzogranitic granodiorites followed; these were intruded by dykes such as B 63 (289 Ma). At this time, the activity appears to have ceased. More differentiated terms, if present at all, are very rare.

The two spectra from the northern samples, B 277 and B 310, are very similar to each other but tell an entirely different story. The pseudoisochron ages are 266.9 ± 7.9 and 269.9 ± 11.1 Ma, only in marginal agreement with B 63. Both spectra feature a staircase shape (Fig. 3), proof of a disturbance in (post-) Jurassic times. This late disturbance may have been present in the whole of Gallura and may be reflected in some "young" literature ages on granitic biotites. Regarding the actual emplacement age, one further constraint is given by VACCARO (1990): other dykes of the low Sr_i group intrude a granite dated at 280 Ma, and must therefore be younger than the high Sr_i group.

Another difference between the northern samples and the southern one is the Cl concentration in the hornblende. Cl is partly transformed to ^{38}Ar during the irradiation, and the Cl content is calculated after partitioning the total ^{38}Ar into components derived from the atmosphere and from irradiation of calcium and potassium. Data can then be displayed in a correlation plot such as figure 4, which shows the Ca/K versus the Cl/K ratio for each step. The straightforward interpretation is

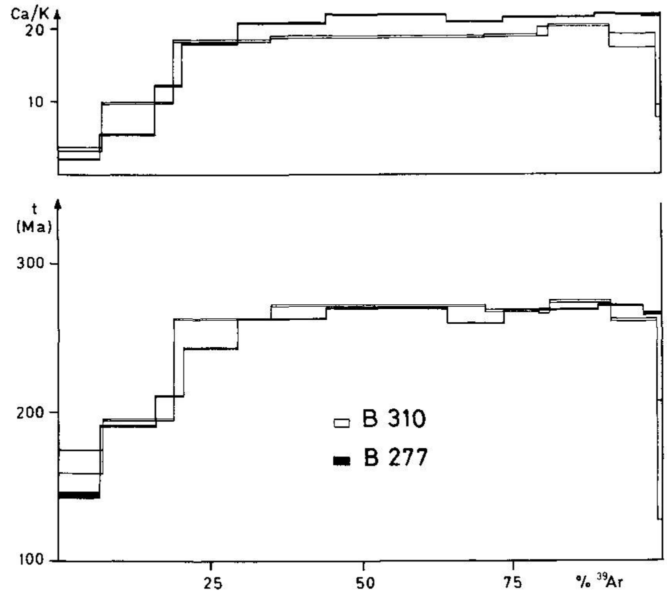

Fig. 3 Age spectra for amphiboles B 277 and B 310. The two samples, collected 20 km apart, are virtually identical. Both show a small disturbance at low step temperature; the flat portion around 270 Ma ("pseudoplateau") is interpreted as the intrusion age.

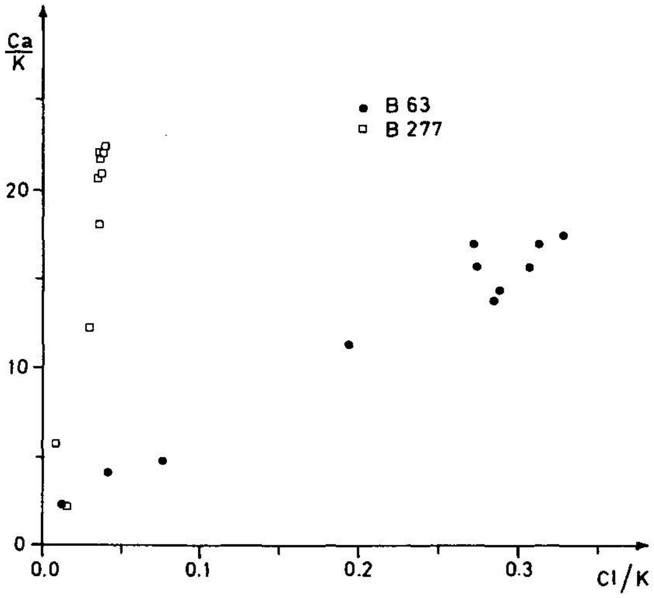

Fig. 4 Three-isotope correlation plot for B 277 and B 63. Ca and Cl are monitored by ^{37}Ar and ^{38}Ar, respectively. The points are approximately aligned; the slope of this alignment is the Ca/Cl ratio in the lattice, which is markedly different in the two samples having a different provenance.

that in all samples (only two are shown for clarity), most of the Cl is unrelated to the K concentration but is instead associated with Ca, in a ratio given by the slope of the line passing through the data points. The very fact that the points define an alignment at all implies that the Cl is a genuine lattice component as are K and Ca. The striking difference of the Cl/Ca ratio is likely to imply a difference in the petrogenesis of the two sets of dykes.

The geographical subdivision between north and south is also evident from the initial Sr isotope ratios. B 277 and B 310 have a lower one (.7067 and .7059, respectively) than the 4 dykes from the S, which range from .7091 to .7105 (see Tab. 1), i.e. fairly common values in most of the Hercynian plutons. The values around .706 determined on the young dykes from Gallura are the lowest among the Hercynian calc-alkaline magmatic products from Sardinia, and similar to those obtained on granodiorites, monzogranites and leucogranites (SW Corsica) by Cocherie (1985).

3.3. ALKALINE DYKES

We analyzed two samples, B 500 and B 216, from the Posada valley, just S of Gallura. Hornblende B 500 was dated by Ar/Ar; due to an oven malfunction 83% of the gas was released in one step giving 238 ± 2 Ma. The age spectrum is similar to those of the calc-alkaline samples in that it is slightly discordant, without large amounts of excess Ar. The isochron has little meaning, owing to the strongly unbalanced gas contents of the steps; the integrated K/Ar age is 236 ± 6 Ma. We also attempted to separate the biotite, but it contained ubiquitous apatite microinclusions, which contain large amounts of common Sr. As a result, the calculated Rb/Sr age is affected by a very high uncertainty, 210 ± 15 Ma. Our best estimate for the age of B 500 is 230 ± 10 Ma. The initial Sr isotopic compositions, corrected for a 230 Ma age, are .7039 ± 1 and .7045 ± 1 for B 500 and B 216, respectively. These low values unambiguously indicate that the parental melts originated in the mantle.

3.4. TRANSITIONAL DYKES

Finally, we analyzed one single quartz-normative dyke, B 227, of the basic-transitional suite. This suite cuts the Permian volcanites (Traversa, 1969); Vaccaro (1990) argued that it was likely to be coeval with the alkaline dykes because transitional and alkaline dykes are associated in non-intersecting en échelon structures. The age-corrected initial Sr isotope ratio is .7052 ± 1, indicating a mantle origin (with a minor crustal contamination) as was the case for the alkaline suite.

4. Discussion

The Hercynian dykes of Sardinia are a rather complex group. The subgroups defined on a petrochemical basis (Atzori and Traversa, 1986) appear to correspond to different stages of the Hercynian tectonic activity, both on structural (Vaccaro, 1990) and on radiometric grounds. Moreover, the different structural provinces of Sardinia appear to have been affected by magmatic episodes belonging to the same subgroup (i.e. tectonic stage) at *different* times.

This work allows to put the first timemarks on this complex history. Granted that the succession of events may have taken place diachronically, we can summarize our sketchy knowledge as follows.

The volumetrically dominant plutons of the calc-alcaline suite range from 305 ± 5 Ma on biotite (Del Moro et al., 1975, recalculated with λ^{87}Rb = 1.42 × 10^{-11}a^{-1}) to 281 ± 5 Ma (Cocherie, 1985) while peraluminous leucogranites range between 303 Ma (Carmignani et al., 1987) and 274 ± 9 Ma (Castorina and Petrini, 1989). We obtained ages for these two petrochemical dyke groups: they also range between 298 ± 5 and 270 ± 10 Ma.

The chronological proximity of the calc-alkaline and peraluminous suites strongly suggests that both pertain to the same thermal crisis that affected the Sardinian basement between 300 and 270 Ma bp.

The structural history of the magmatic complex has been described by GHEZZO and ORSINI (1982) as consisting of 3 phases: (i) syntectonic: pervasively affected by regional deformation; (ii) late-tectonic: locally oriented; (iii) post-tectonic: lacking deformation and intruded discordantly to schistosity.

The main criterion, to distinguish between (i) and (ii) should be the presence of an uniform, pervasive deformation, rather than the maximum local deformation, as shears can attain very high localized intensities much after the end of the regional phase.

The plutons cut by the dykes considered in the present work all belong to the late- to post-tectonic phase, as none shows uniform pervasive deformation: some are locally deformed, some are totally undeformed. The dykes cutting them are mostly undeformed; only a small minority shows quartz and/or K-feldspar ribbons and non-penetrative grain boundary recrystallization. It appears from their structure that most of the calc-alkaline and peraluminous dykes are later than the shear movements and seal off the local tectonic activity. This allows to bracket the timing of the shearing for each pluton-dyke association; as the latter are only marginally younger than the former, the implications that the local deformation field which accompanied the intrusion of the late-tectonic granites petered off very rapidly.

Several samples (those from the N and those from the shear zone near Mt Grighini) show evidence of a post-crystallization disturbance; this disturbance cannot be dated directly, but is constrained by the combined pattern of the present data to be no older than Jurassic. While the high Sr_i calc-alkaline dykes frequently cross-cut both each other and the peraluminous dykes and form multiple intrusions, dykes from the low Sr_i group in the north form en échelon structures whose elements do not intersect. They are only cut by the alkaline and transitional undeformed dykes, whose only radiometric age is younger by about 40 Ma.

The Sr isotopic data allow to recognize an evolutive trend for the magmas. The peraluminous dykes have initial Sr isotopic ratio between .7100 and .7165. As we have discussed above, they most likely derive from partial fusion of a pelitic source material. Although some of the Sr data were obtained from whole rocks which have a comparatively high Rb/Sr ratio, i.e. are far from the ordinate axis (so that the initial Sr isotopic composition has a high uncertainty), the variations we are trying to interpret are much larger than the analytical errors.

The calcalkaline dykes, on the other hand, fall into two subgroups. The first one is characterized by higher Sr isotopic composition, which may be explained by a larger crustal involvement, and by $\Sigma REE > 150$ ppm; it occurs both in the northern and southern sector. These dykes are oldest both in the field and radiometrically. The high Sr_i in the "old" calcalkaline dykes relates them to the main mass of the batholith.

The second subgroup has lowest Sr_i and highest Sr concentration; this makes it unlikely that their Sr was prone to modification by addition of secondary Sr. Thus, their source material had $^{87}Sr/^{86}Sr < 0.7059$, incompatible with metasedimentary protoliths and characteristic of lower crustal or metasomatized mantle enviroments. The ΣREE ranges between 50 and 120 ppm. This subgroup occurs only in the north, and is younger than the first one.

The last episodes – transitional and alkaline dykes – have the lowest Sr_i, possibly with negligible crustal contribution. They point to a transitional, post-orogenic tectonic regime during which subcrustal magmas gained access to the surface through a thinned continental crust.

5. Conclusions

We analyzed and dated dykes belonging to 4 petrochemical groups.

The oldest group consists of peraluminous and high-Sr_i calcalkaline dykes. Their ages, 298 ± 5 to 289 ± 4 Ma, are only slightly younger than the late-tectonic plutons of the batholith which they intrude. Most of these dykes are weakly tectonized. A major chronological and chemical discontinuity separates a northern and a southern tectonic domain (cfr. also EDEL et al., 1981). In the south, no magmatic activity occurred later than 290 Ma (except for subalkaline dykes in Sarrabus in the extreme southern end) and the exhumation of the orogen was very limited. On the contrary, a remarkable exhumation took place in the northern sector; as a result the tectonic style and the isotopic and chemical characteristics of the dykes underwent a progressive change.

Low-Sr_i calcalkaline dykes intrude around 270 Ma, and testify that the magma feeding reaches deeper levels, possibly owing to crustal thinning. The contribution of fresh mantle is highest in the ca. 230 Ma old transitional and alkaline dykes, whose post-orogenic character concludes the Hercynian orogeny in Sardinia.

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Appendix Sample location and description.

Sample	Locality	Classification	Paragenesis	Strike / Dip	Thickness (m)
B 50	Arbatax Harbour quarry	Basic calc-alkaline dyke high-K low-Si andesite	Pl-Kf-Qz-Amph- Ores-Accessories	N-S / vertical	3
B 63	Road Tortolì- Villagrande	Calc-alkaline dyke high-K andesite	Pl-Qz-Bi-Amph- Ores-Accessories	N30W-S30E / vertical	1.5
B 108	Road Atzara - Ortueri, 200 m after Pedas junction	Peraluminous ultra-acid dyke rhyolite	Qz-Kf-Pl-Mu-Bi	N15E-S15W / N75W, 45°	1
B 128	Road Dorgali - Baunei 18 km from Baunei	Peraluminous ultra-acid dyke rhyolite	Qz-Kf-Pl-Mu-Bi	N30E-S30W / vertical	1.5
B 210	Road Pattada - Oschiri half way	Calc-alkaline dyke rhyolite	Qz-Kf-Pl-Bi-Groundmass	N40W-S40E / vertical	1
B 216	Road Alà dei Sardi - Piras 7.6 km from Alà	Alkaline dyke alkalibasalt	Pl- brown & green Amph- Ores-altered mafics	N70W-S70E / N20E, 25°	6
B 227	Road Alà dei Sardi - Padru Sa Pedra Bianca junction	Basic-transitional, Qz-norm dyke basalt	Pl-Amph-Cpx-Ores- altered mafics	N-S / E, 80°	1
B 269	Road S. Antonio di Gallura - Arzachena, 4 km N of S.Ant.	Peraluminous ultra-acid dyke rhyolite	Qz-Kf-Pl-Mu-Bi	N60E-S60W / vertical	1
B 277	Road Aggius - Palau, S. Maria delle Grazie junction	Calc-alkaline dyke high-K low-Si andesite	Pl-Cpx-Amph-Ores- altered mafics	N10E-S10W / vertical	2
B 310	Near S. Teresa di Gallura	Calc-alkaline dyke high-K low-Si andesite	Pl-Cpx-Amph-Ores- altered mafics	N50E-S50W / vertical	1.5
B 500	Bruncu Nieddu, between Lodè and Siniscola	Alkaline dyke alkalibasalt	Amph-Bi-Ap-altered mafics-minute groundmass	N-S / vertical	2.5
SC 24	Mt. Lerno	Peraluminous ultra-acid dyke rhyolite	Mu-Qz-Kf	N10W-S10E / S80W, 70°	0.5
SC 52	Concas	Leucogranite (deformed border facies)	Qz-Kf-Pl-Mu-Bi-Gt		
SC 131	Concas	Leucogranite (undeformed)	Qz-Kf-Pl-Mu-Bi-Gt		