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Autor: Villa, Igor M. / Blanckenburg, Friedhelm von

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A hornblende ^{39}Ar–^{40}Ar age traverse of the Bregaglia tonalite (southeast Central Alps)

by *Igor M. Villa*[1] and *Friedhelm von Blanckenburg*[2]

Abstract

An east-west age traverse along the Bregaglia (Bergell) tonalite was established with six hornblende ages obtained by ^{40}Ar–^{39}Ar stepwise heating and six K–Ar ages on biotite. Geobarometry indicates a crystallization depth of 18 km for the eastern and 27 km for the western hornblendes. Biotite ages decreasing from 26.4 Ma in the E to 21.0 in the W reflect this depth gradient – clearly an effect of post-regional metamorphic cooling and later uplift of the western and more deeply buried part of the intrusion. Hornblende release spectra display constant Ca/K over 95% of the release indicating that homogeneous minerals were dated. None of them, however, yields a regular age plateau. The discordant spectra are caused by inhomogeneously distributed excess Ar. Two hornblendes yield statistically valid isochron ages around 29 Ma for the easternmost and a central sample. In light of new U–Pb intrusion ages of 31.9 Ma for the tonalite and 30.1 Ma for the granodiorite these hornblende ages indicate that postmagmatic cooling was rather slow (~ 90 °C/Ma). Age estimates from the discordant spectra of the two westernmost hornblendes are about 24–26 Ma. Several scenarios can be envisaged for this age gap in cooling ages. The most likely explanation is a different relative timing of magmatism and metamorphism in the different structural levels presently exposed: in the E, postmagmatic cooling was superimposed on regional metamorphic cooling from a preintrusive metamorphic climax; in the W, postintrusive cooling was delayed because it was *followed* by the regional metamorphic climax. Further refinements are unsupported in light of the high uncertainty of the ages introduced by excess Argon, which is larger than the *analytical* error, and the interference of metamorphism, magmatism, and tectonism in the area.

Keywords: ^{39}Ar–^{40}Ar geochronology, Central Alps, Bregaglia/Bergell, Alpine metamorphic events, Periadriatic magmatism.

1. Introduction

The reconstruction of the thermal history of the Oligocene Bregaglia intrusion is complicated because of the interference of magmatism and simultaneous metamorphism. An effect of this interference is that the regional metamorphic isograds marking the distribution of this Tertiary "Lepontine" metamorphism are usually mapped around the eastern margin of the intrusion (JÄGER et al., 1967; TROMMSDORFF, 1966), although this eastern continuation of the isograds may well be a result of contact metamorphism induced by the intrusion (BUCHER-NURMINEN, 1977). One possibility to distinguish between the regional and the contact metamorphism is establishing their timing by using a geochronometer having a intermediate to high retentivity, such as hornblende. Hornblende data for the Bregaglia tonalite were so far restricted to K–Ar ages (DEUTSCH and STEIGER, 1985; WIEDENBECK and BAUR, 1986; GIGER and HURFORD, 1989) and range from 29.6 up to 37 Ma. The latter is an unlikely age as the intrusion age for the tonalite was determined precisely by high resolution zircon U–Pb geochronology to be 31.9 ± .09 Ma (VON BLANCKENBURG, 1990). Hornblendes with their low K-concentrations are extremely sensitive to excess Ar (VON BLANCKENBURG and VILLA, 1988) and it appears that conventional K–Ar dating of hornblende is inadequate to achieve the high time resolution necessary to resolve the small age differences which are of interest. The ^{39}Ar–^{40}Ar stepwise heating technique has the potential to identify excess Ar. In this study we will attempt to reduce the

[1] Istituto di geocronologia e geochimica isotopica, Via Cardinale Maffi 36, I-56100 Pisa, Italy.
[2] Institut für Kristallographie und Petrographie, ETH-Zentrum, CH-8092 Zürich, Switzerland.
Present address: Department of Earth Sciences, University of Cambridge, Downing Street, Cambridge CB23EQ, UK.

uncertainty affecting age assignments by dating six hornblendes by ^{39}Ar–^{40}Ar along an E–W traverse, supplemented by K–Ar dating of six coexisting biotites.

2. Geological and geochronological framework

The Bregaglia intrusion is located in the southeastern part of the Central Alps (Fig. 1). It consists of small, marginal occurrences of early differentiated hornblendites and gabbros (DIETHELM, 1989), a frame and a southern band of tonalite and a core of granodiorite. The tonalite is rather massive in the east and becomes gradually more foliated towards the west. A branch of this foliated tonalite extends 60 km to the west ("Iorio tonalite", WEBER, 1957). The eastern stock discordantly intruded the already greenschist-metamorphosed country rock in the east developing a pronounced contact aureole (TROMMSDORFF and EVANS, 1972), while in the west intrusional contacts are concordant with the amphibolite to sillimanite facies country rock in which no contact metamorphism has been observed. A detailed description of the geological features and the field relations of the intrusion is given by TROMMSDORFF AND NIEVERGELT (1983).

New results have become available since. From hornblende barometry, REUSSER (1987) deduced a crystallization depth of 18 km in the east and 27 km in the west for the hornblendes of the tonalite. This is in accordance with TROMMSDORFF and NIEVERGELT (1983) who calculated an increased overburdening of ca. 10 km by the Alpine nappes which are crosscut by the intrusion and with SCHMID et al. (1989) who argues for a delay in the uplift of the Central Alpine area west of the Bregaglia which resulted in a tilting of the intrusion around a N–S oriented axis. Dextral movements along the Insubric line, which changed gradually into a vertical backthrusting of the Central Alps over the Southern Alps, produced subhorizontal E–W trending stretching lineations between the Iorio tonalite and the Insubric line and steeply northward plunging lineations in the Iorio tonalite itself (FISCH, 1989). Later brittle deformation along the dextral Tonale fault (HEITZMANN, 1987), produced the "Riedel-shears" which crosscut the tonalite (Fig. 1).

Based on the petrological results of DIETHELM (1989) and Nd-, Sr-, and oxygen isotope data by VON BLANCKENBURG (1990) the intrusion was initiated by basaltic magmatism originating from a subcontinental, slightly contaminated mantle, and fractionated to produce the relatively uncontaminated early differentiates. Increasing assimilation of crustal rocks produced the tonalite, granodiorite, aplites, pegmatites, and the Melirolo Augengneiss. The younger Novate leucogranite appears to originate from a different, highly crustal source.

The granodiorite intrusion was dated at 30 Ma by GULSON and KROGH (1973), new U–Th–Pb ages of accessory minerals from an eastern tonalite sample (Siss 3) and a closeby granodiorite yielded a zircon age of 31.9 ± .09 Ma for the tonalite intrusion and ages of 30.1 ± .17 Ma for allanite and sphene from the granodiorite which experienced no lead loss (VON BLANCKENBURG, 1990). The age of the Tertiary metamorphism is 35–40 Ma in the Surettanappe to the north of the intrusion (HURFORD et al., 1989), while to the west 38 ± 2 Ma (JÄGER, 1973) or 26 ± 3 Ma (DEUTSCH and STEIGER, 1985) were proposed. These rocks were uplifted to shallow levels as recently as 14 Ma ago according to apatite fission track dating (WAGNER et al., 1979; GIGER and HURFORD, 1989).

3. Analytical techniques

Electron microprobe data (Tab. 1) were obtained on polished sections of each sample using the ETH-Zurich Cameca SX50 microprobe operated with wave length dispersive systems.

Hornblende and biotite were separated using standard techniques and sieved to grain size fractions of 75–180 µm and 180–500 µm, respectively, because pure separates were obtained at these sieve sizes. Minerals were handpicked once before analysis.

Biotites were analyzed by K–Ar following DEL MORO et al. (1982). No stepwise heating was attempted, following the conclusions of FOLAND (1983).

Hornblendes were irradiated in the McMasters reactor, Canada, position 5C. The flux gradient over the whole 4 cm irradiation canister was 1.9%, controlled by two Fish Canyon Tuff biotite monitors (27.55 Ma, LANPHERE et al., 1990). Samples were heated stepwise by radiofrequency in a machined Mo crucible. The crucible temperatures are probably accurate to ± 3%, but temperature *differences* are likely to be much preciser. Data are presented in Tab. 2 and corrected for machine background, discrimination, and ^{37}Ar decay corrections only, but not for blanks. These were *always* of atmospheric composition and amounted to 0.8 pl below 1100 °C gradually rising to 8 pl at 1600 °C. Tab. 2 contains no blank correction, so as not to introduce an additional uncertainty which might smear significant inter-step differences. Step ages and isochron plots were calculated after additionally correcting for interferences; the most relevant parameters were: $(^{39}Ar/^{37}Ar)_{Ca} = 6.5\times10^{-4}$;

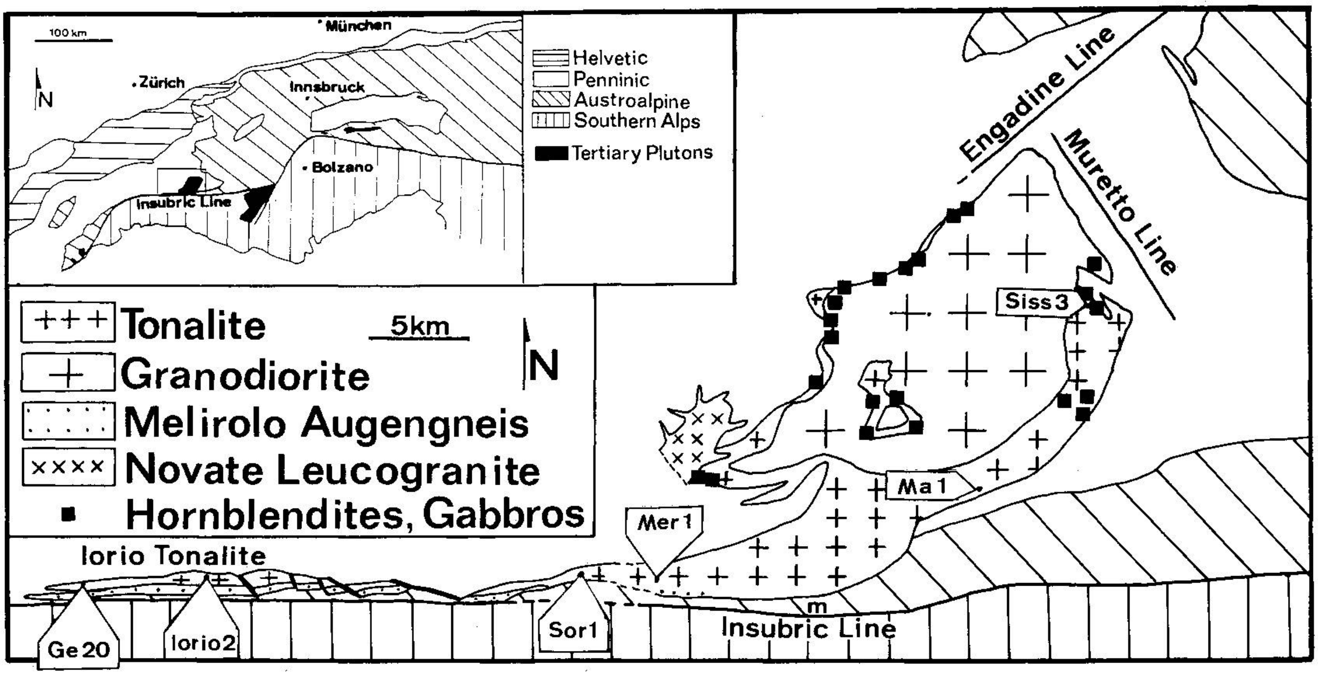

Fig. 1 Simplified geological sketch map of the Bregaglia intrusion after TROMMSDORFF and NIEVERGELT (1983), WEBER (1957) and DIETHELM (1989). m = Mello. Sample locations are Siss 3: Val Sissone; Ma 1: Val Masino; Mer 1: Val Mera; Sor 1: Sorico; Iorio 2: Passo San Iorio: Ge 20: Alpe Gesero. Exact sample locations are given in VON BLANCKENBURG (1990).

$(^{36}Ar/^{37}Ar)_{Ca} = 2.55 \times 10^{-4}$; $(^{38}Ar/^{39}Ar)_K = 0.014$; Cl/K = $(^{38}Ar_{Cl}/^{39}Ar_K) \times 0.25$; Ca/K = $(^{37}Ar_{Ca}/^{39}Ar_K) \times 1.8$ (ONSTOTT and PEACOCK, 1987; ONSTOTT, T.C., pers. comm.). Potassium, chlorine and calcium abundances calculated from Ar data shown in Tab. 2 closely agree with microprobe data. The problem of the correct correction for blank contamination will be addressed elsewhere (VILLA, in prep.). Fortunately, correcting or not correcting for blank turns out not to make any difference in the case of hornblende Siss 3: on this crucial sample, we compared the isochron age obtained without any blank correction with that obtained after blank subtracting; the age difference was 1‰, much smaller than the internal error of the fit, 6‰.

When compared to other dating results, an additional error of 1% should be propagated into the ages to account for the absolute and relative flux uncertainties: the uncertainty of the relative fluxes is very conservatively estimated at 0.3% (this error was omitted in the data presented in Tab. 2 to allow the assessment of the significance of internal discordance, but should be included for inter-sample comparison [Fig. 4]); the published uncertainty on the Fish Canyon Tuff monitor is now 0.3% (LANPHERE et al., 1990). However, we feel that a total error of 1% accounts better for inter-method calibration. Errors in Tab. 2 and 3 and all figures are 2-sigma, isochron errors are at the 95% confidence level.

4. Results

4.1. MICROPROBE RESULTS FOR HORNBLENDE AND BIOTITE

A thorough analysis and discussion of the chemical composition of tonalite minerals is given by REUSSER (1987), thus only a short description of the dated minerals is given here for completeness. Microprobe analyses are given in Tab. 1. In general, amphiboles are magnesio-hornblendes (LEAKE, 1978) and plot in the medium- to high-temperature field of LAIRD and ALBEE (1981). This is in agreement with the hornblendes being of magmatic or high temperature subsolidus origin. Biotites are about 60% phlogopites with up to 0.2 tschermak exchange component per formula unit.

4.2. HORNBLENDE STEPHEATING DATA

Hornblende ^{39}Ar–^{40}Ar release spectra are shown in Fig. 2. In general, all age spectra show considerable irregularities and no straightforward age information can be obtained from them. The spectra are generally "saddles", i.e. the steps with the lowest ages are preceded and followed by steps having significantly higher ages. Interestingly, the $^{37}Ar/^{39}Ar$-derived Ca/K spectra show irregularities in the first five percent of the release, which may be due to < 1% of unseparable or submicroscopic biotite,

Tab. 1 Microprobe data of dated hornblendes and biotites. Core and rim were given separately only if differences were found. The normalizing procedures are discussed by REUSSER (1987).

Tonalite hornblende analyses

Sample	Siss3-core	Siss3-rim	Mal	Merl-core	Merl-rim	Sorl	Iorio2	Ge20 -core	Ge20 -rim
SiO2	44.76	42.83	41.53	44.11	43.05	45.15	45.19	44.25	40.89
TiO2	1.95	1.11	0.61	1.42	0.77	0.98	1.43	0.92	0.83
Cr2O3	0.00	0.02	0.04	0.00	0.02	0.00	0.01	0.00	0.07
Al2O3	8.48	9.95	12.08	9.51	10.54	11.08	9.00	10.34	12.94
Fe2O3	4.35	5.08	4.15	5.30	5.13	6.34	4.72	2.47	3.96
FeO	11.66	13.22	13.62	11.80	11.18	10.37	10.45	13.08	13.27
MnO	0.38	0.39	0.47	0.50	0.36	0.32	0.46	0.41	0.31
MgO	12.07	10.38	9.71	11.21	11.05	11.62	12.25	11.15	9.47
CaO	11.78	12.04	12.31	11.87	11.89	11.73	11.79	12.25	11.76
Na2O	1.24	1.09	1.17	1.14	1.13	1.20	1.23	1.01	1.33
K2O	1.05	1.27	1.36	0.96	0.92	1.08	0.60	1.21	1.65
Cl	0.16	0.13	0.15	0.18	0.15	0.13	0.07	0.06	0.11
H2O	1.98	1.95	1.94	1.97	1.95	2.04	2.01	1.99	1.94
Total	99.87	99.46	99.16	99.96	98.14	102.05	99.20	99.13	98.53
Cl-O	0.04	0.03	0.03	0.04	0.03	0.03	0.02	0.01	0.02
Total	99.84	99.43	99.12	99.92	98.10	102.02	99.18	99.12	98.50
CATIONS calculated on the basis of 23 oxygens and 13 cations + K + Na + Ca									
Si	6.6448	6.4675	6.3036	6.5635	6.5035	6.5226	6.6903	6.6210	6.2337
Ti	0.2181	0.1265	0.0697	0.1591	0.0874	0.1068	0.1589	0.1032	0.0957
Cr	0.0000	0.0025	0.0044	0.0000	0.0026	0.0000	0.0007	0.0000	0.0081
Al	1.4844	1.7703	2.1614	1.6670	1.8761	1.8863	1.5696	1.8233	2.3246
Fe3	0.4863	0.5778	0.4740	0.5937	0.5832	0.6895	0.5261	0.2777	0.4547
Fe2	1.4477	1.6693	1.7292	1.4680	1.4127	1.2533	1.2938	1.6368	1.6920
Mn	0.0482	0.0495	0.0608	0.0628	0.0464	0.0394	0.0573	0.0521	0.0399
Mg	2.6705	2.3365	2.1968	2.4859	2.4880	2.5021	2.7033	2.4859	2.1512
Ca	1.8740	1.9488	2.0024	1.8918	1.9242	1.8148	1.8694	1.9636	1.9207
Na	0.3560	0.3198	0.3449	0.3280	0.3307	0.3364	0.3525	0.2927	0.3916
K	0.1994	0.2439	0.2637	0.1824	0.1771	0.1994	0.1139	0.2307	0.3207
Cl	0.0398	0.0325	0.0388	0.0449	0.0392	0.0308	0.0173	0.0165	0.0274
OH	1.9602	1.9675	1.9612	1.9551	1.9608	1.9692	1.9827	1.9835	1.9726
SITE distribution and RATIOS									
xMg (FeII+)	0.648	0.583	0.560	0.629	0.638	0.666	0.676	0.603	0.560
Al(IV)	1.355	1.532	1.696	1.436	1.496	1.477	1.310	1.379	1.766
Al(VI)	0.129	0.238	0.465	0.231	0.380	0.409	0.260	0.444	0.558
Na(M4)	0.126	0.051	0.000	0.108	0.076	0.185	0.131	0.036	0.079
Na(A)	0.230	0.269	0.345	0.220	0.255	0.151	0.222	0.256	0.312
Fe3+/Fe(tot)	0.251	0.257	0.215	0.288	0.292	0.355	0.289	0.145	0.212

Tonalite biotite analyses

Sample	Siss3	Mal	Merl	Sorl	Iorio2	Ge20
SiO2	36.72	36.44	36.69	36.50	36.25	36.04
TiO2	2.43	2.65	2.64	2.35	2.55	1.57
Cr2O3	0.00	0.00	0.00	0.00	0.00	0.00
Al2O3	15.35	16.04	15.43	15.02	16.35	15.88
Fe2O3	3.23	2.84	1.29	2.48	3.07	1.09
FeO	15.51	15.15	15.24	14.70	13.35	17.28
MnO	0.24	0.25	0.31	0.25	0.16	0.35
MgO	12.68	12.38	12.96	12.90	13.34	12.08
CaO	0.03	0.03	0.33	0.08	0.02	0.07
Na2O	0.07	0.12	0.13	0.15	0.18	0.09
K2O	9.48	9.30	9.26	8.90	9.14	9.17
Cl	0.08	0.12	0.10	0.09	0.04	0.08
H2O	3.96	3.95	3.92	3.89	3.97	3.86
Total	99.76	99.27	98.31	97.31	98.42	97.57
Cl-O	0.02	0.03	0.02	0.02	0.01	0.02
Total	99.74	99.24	98.28	97.29	98.41	97.55
CATIONS calculated with 11 oxygens and cations - Na - K = 7 - Ti						
Si	2.7652	2.7484	2.7876	2.7974	2.7327	2.7818
Ti	0.1374	0.1504	0.1510	0.1357	0.1448	0.0910
Cr	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Al	1.3620	1.4255	1.3810	1.3565	1.4529	1.4443
Fe3	0.1828	0.1612	0.0738	0.1430	0.1739	0.0635
Fe2	0.9768	0.9558	0.9679	0.9419	0.8419	1.1157
Mn	0.0152	0.0162	0.0202	0.0159	0.0103	0.0228
Mg	1.4231	1.3921	1.4673	1.4740	1.4988	1.3900
Ca	0.0020	0.0021	0.0267	0.0066	0.0019	0.0061
Na	0.0096	0.0174	0.0191	0.0221	0.0257	0.0139
K	0.9111	0.8949	0.8974	0.8704	0.8784	0.9025
Cl	0.0096	0.0152	0.0130	0.0122	0.0047	0.0109
OH	1.9904	1.9848	1.9870	1.9878	1.9953	1.9891
SITE distribution and RATIOS						
xMg (FeII+)	0.593	0.593	0.603	0.610	0.640	0.555
Al(IV)	1.235	1.252	1.212	1.203	1.267	1.218
Al(VI)	0.127	0.174	0.169	0.154	0.186	0.226
Fe3+/Fe(tot)	0.158	0.144	0.071	0.132	0.171	0.054

Tab. 2 Hornblende stepheating data. Errors are 2 sigma and only reflect in-run statistics. Values are corrected for discrimination, background, and ^{37}Ar decay. "Totals" were calculated from the production rates and the total of all steps. All isotopes are in pl/g, equivalent to $10^{-12}m^3/kg$ mineral. K and Ca are in weight%, Cl in ppm.

Siss 3 0.2176 g J = .001182

T (°C)	$^{40}Ar_{tot}$	^{39}Ar	^{38}Ar	^{37}Ar	^{36}Ar	t (Ma)
750	149.9 ± .2	0.526 ± 6	0.526 ± 4	0.80 ± 2	0.4428 ± 48	75.76 ±5.54
860	15.55 ± 2	0.361 ± 4	0.108 ± 2	1.15 ± 4	0.0381 ± 18	25.69 ±3.16
970	91.15 ± 8	4.344 ± 14	2.692 ± 14	22.3 ± .2	0.1124 ± 22	29.17 ± .32
1000	161.4 ± .4	9.002 ± 26	6.142 ± 30	43.3 ± .2	0.1301 ± 22	29.79 ±.18
1020	310.4 ± .8	18.908 ± 42	13.335 ± 50	91.8 ± .6	0.1871 ± 26	29.44 ±.12
1030	215.1 ± .4	13.811 ± 32	9.526 ± 40	65.9 ± .4	0.1042 ± 24	29.11 ±.12
1040	164.0 ± .4	10.917 ± 30	7.526 ± 32	51.8 ± .4	0.0640 ± 18	29.00 ±.12
1060	107.6 ± .2	7.257 ± 22	4.964 ± 22	34.1 ± .2	0.0382 ± 14	28.96 ±.12
1080	88.59 ±.32	5.807 ± 48	3.917 ± 18	27.0 ± .4	0.0369 ± 18	29.16 ±.30
1100	70.41 ± .10	4.519 ± 14	2.970 ± 16	21.5 ± .2	0.0328 ± 10	29.31 ±.16
1120	51.79 ± 6	3.177 ± 12	2.112 ± 10	15.5 ±.2	0.0295 ± 12	29.59 ±.22
1140	26.86 ± 4	1.564 ± 8	1.062 ± 10	7.46 ± 8	0.0167 ± 12	30.53 ±.44
1160	8.27 ± 2	0.425 ± 4	0.298 ± 4	1.31 ± 2	0.0097 ± 14	27.44 ±2.02
1180	9.29 ± 2	0.462 ± 4	0.316 ± 4	2.16 ± 4	0.0106 ± 8	29.04 ±.98
1250	25.78 ± 4	1.044 ± 6	0.717 ± 4	4.99 ± 6	0.0379 ± 14	30.39 ±.86
1500	13.26 ± 2	0.086 ± 2	0.054 ± 2	0.33 ± 2	0.0411 ± 6	28.18 ±4.98
Total	($^{40}Ar^*$=1147)	(K=0.99)	(Cl=1368)	(Ca=8.6)		29.59

Ma 1 0.2043 g J = .001186

T (°C)	$^{40}Ar_{tot}$	^{39}Ar	^{38}Ar	^{37}Ar	^{36}Ar	t (Ma)
800	367.7 ± .6	0.497 ± 4	0.987 ± 6	1.31 ± 4	0.9199 ± 84	372.5 ± 9.4
900	48.42 ± 4	0.364 ± 4	0.168 ± 2	0.87 ± 4	0.1371 ± 16	46.44 ±2.78
950	21.69 ± 4	0.288 ± 2	0.201 ± 2	1.16 ± 4	0.0565 ± 12	37.53 ±2.58
1000	116.3 ± .2	4.104 ± 12	3.815 ± 18	18.4 ± .2	0.1917 ± 22	31.67 ± .36
1050	243.0 ± .4	10.698 ± 28	9.860 ± 38	46.9 ± .2	0.2555 ± 40	34.02 ± .24
1080	417.5 ± .6	20.202 ± 56	18.241 ± 72	90.1 ± .6	0.3485 ± 60	33.85 ± .20
1110	418.0 ± .8	25.083 ± 64	21.648 ± 86	109.5 ± .6	0.2237 ± 46	30.59 ± .14
1130	110.8 ± .2	6.445 ± 24	5.448 ± 26	27.5 ± .2	0.0680 ± 12	30.67 ± .16
1150	127.0 ± .2	6.933 ± 22	5.928 ± 28	30.1 ± .2	0.0865 ± 22	31.86 ± .22
1180	206.0 ± .4	11.636 ± 32	9.755 ± 40	48.7 ± .2	0.1130 ± 12	32.26 ± .12
1200	32.84 ± 4	1.663 ± 8	1.410 ± 6	7.12 ± 6	0.0289 ± 20	31.78 ± .70
1300	28.97 ± 4	1.483 ± 10	1.259 ± 8	6.21 ± 6	0.0239 ± 12	32.14 ± .54
1400	32.75 ± 6	1.140 ± 6	0.973 ± 8	4.74 ± 6	0.0529 ± 18	32.65 ± .98
1600	36.81 ± 4	0.133 ± 2	0.118 ± 4	0.48 ± 4	0.1196 ± 26	23.94 ±12.26
Total	($^{40}Ar^*$=1464)	(K=1.08)	(Cl=2022)	(Ca=9.4)		34.33

Tab. 2 (cont.)

Mer 1 0.1938 g J = .001189

T (°C)	$^{40}Ar_{tot}$	^{39}Ar	^{38}Ar	^{37}Ar	^{36}Ar	t (Ma)
850	236.4 ± .2	0.764 ± 8	1.526 ± 30	1.74 ±.16	0.5558 ± 64	192.54 ± 5.06
950	31.08 ± 4	0.577 ± 4	0.243 ± 4	1.22 ± 4	0.0759 ± 18	32.35 ±1.86
1000	61.80 ± .10	1.616 ± 12	1.272 ± 10	6.57 ±.16	0.1279 ± 12	32.35 ± .56
1080	104.2 ± .2	5.047 ± 18	5.012 ± 22	25.3 ± .2	0.1100 ± 26	31.14 ± .30
1100	185.3 ± .2	9.551 ± 32	9.474 ± 38	48.0 ± .6	0.1536 ± 34	32.10 ± .12
1120	477.9 ± 1.0	28.024 ± 60	26.367 ± .108	134.6 ± 1.0	0.2944 ± 52	30.59 ± .14
1140	167.4 ± .2	10.468 ± 30	9.520 ± 38	48.4 ± .4	0.0912 ± 18	29.38 ± .12
1160	51.46 ± 8	2.908 ± 16	2.657 ± 20	13.2 ± .2	0.0396 ± 10	29.95 ± .24
1180	41.51 ± 6	2.130 ± 16	2.005 ± 10	10.2 ± .2	0.0413 ± 10	30.17 ± .36
1200	54.18 ± 8	2.868 ± 12	2.696 ± 12	14.0 ± .2	0.0479 ± 16	30.61 ± .32
1250	95.95 ± .18	5.129 ± 16	4.683 ± 20	23.7 ± .2	0.0757 ± 18	31.38 ± .22
1400	65.98 ± 8	2.459 ± 12	2.262 ± 12	11.3 ± .2	0.1057 ± 22	30.91 ± .56
1600	48.89 ± 8	0.147 ± 2	0.151 ± 2	0.71 ±.16	0.1536 ± 38	50.54 ±15.58
Total	($^{40}Ar^*$=1100)	(K=0.86)	(Cl=1748)	(Ca=8.5)		32.59

Sor 1 0.2408 g J = .001194

T (°C)	$^{40}Ar_{tot}$	^{39}Ar	^{38}Ar	^{37}Ar	^{36}Ar	t (Ma)
750	176.0 ± 5.2	0.585 ± 66	2.003 ±.322	3.82 ±.34	0.4216 ± 88	181.5 ±22.0
850	108.2 ± .2	1.243 ± 11	0.501 ± 9	1.59 ± 9	0.2540 ± 38	56.78 ±1.92
950	23.13 ± 6	0.433 ± 4	0.189 ± 6	1.18 ± 8	0.0548 ± 8	34.61 ±1.14
1000	24.96 ± 4	0.626 ± 6	0.357 ± 6	2.65 ± 8	0.0567 ± 18	28.80 ±1.76
1030	32.70 ± 6	1.156 ± 8	0.901 ± 8	6.14 ± 10	0.0584 ± 12	29.55 ± .68
1050	54.20 ± 6	2.364 ± 12	2.117 ± 8	13.4 ± .2	0.0679 ± 16	31.93 ± .44
1080	197.2 ± .4	10.156 ± 26	9.128 ± 48	56.8 ± .6	0.1751 ± 24	31.66 ± .16
1100	188.1 ± .2	9.965 ± 20	8.803 ± 38	54.9 ± .6	0.1481 ± 36	31.96 ± .22
1120	165.3 ± .2	8.866 ± 22	7.826 ± 36	48.2 ± .6	0.1257 ± 36	31.91 ± .14
1140	145.1 ± .4	7.893 ± 28	6.946 ± 38	42.7 ± .2	0.1106 ± 28	31.47 ± .30
1160	120.2 ± .2	6.565 ± 20	5.683 ± 26	35.1 ± .6	0.0922 ± 20	31.25 ± .22
1180	177.9 ± .2	9.805 ± 28	8.498 ± 34	51.4 ± .8	0.1292 ± 34	31.45 ± .22
1250	113.1 ± .2	5.965 ± 18	5.206 ± 26	31.6 ± .2	0.0852 ± 30	32.49 ± .30
1300	79.20 ± 8	3.841 ± 20	3.350 ± .28	20.3 ± .2	0.0756 ± 18	32.63 ± .32
1400	116.7 ± .2	4.125 ± 18	3.603 ± 18	21.6 ± .2	0.1867 ± 28	32.87 ± .42
1600	56.74 ± 6	0.189 ± 2	0.188 ± 2	1.88 ± 8	0.1800 ± 30	42.21 ±10.36
Total	($^{40}Ar^*$=1154)	(K=0.88)	(Cl=1642)	(Ca=8.4)		33.29

Tab. 2 (cont.)

Iorio 2 0.2608 g J = .001200

T (°C)	$^{40}Ar_{tot}$	^{39}Ar	^{38}Ar	^{37}Ar	^{36}Ar	t (Ma)
850	236.4 ± .2	0.609 ± 4	0.323 ± 4	1.51 ±.10	0.5584 ± 46	238.2 ± 4.6
950	34.07 ± 2	0.321 ± 2	0.072 ± 2	1.14 ± 4	0.0936 ± 22	43.52 ±4.52
1000	16.16 ± 2	0.268 ± 2	0.088 ± 2	1.68 ±.10	0.0418 ± 12	31.87 ±3.12
1030	14.63 ± 2	0.344 ± 2	0.135 ± 2	2.39 ± 8	0.0355 ± 8	27.12 ±1.46
1050	24.70 ± 4	0.878 ± 4	0.399 ± 4	6.02 ±.18	0.0495 ± 18	25.99 ±1.20
1080	44.55 ± 4	1.959 ± 10	0.902 ± 8	14.0 ± .2	0.0742 ± 18	26.17 ± .54
1100	105.6 ± .2	5.022 ± 18	2.292 ± 10	37.1 ± .4	0.1389 ± 18	29.03 ± .22
1120	211.6 ± .2	12.157 ± 32	5.347 ± 22	89.0 ± .8	0.2166 ± 34	27.47 ± .18
1140	44.44 ± 8	2.554 ± 52	1.120 ± 10	18.0 ± .2	0.0503 ± 8	26.23 ± .18
1160	30.06 ± 4	1.474 ± 8	0.653 ± 8	10.4 ± .2	0.0430 ± 10	26.62 ± .42
1180	56.42 ± 8	3.149 ± 12	1.384 ± 10	22.0 ± .2	0.0700 ± 20	25.71 ± .38
1250	188.9 ± .2	11.205 ± 40	4.893 ± 22	78.5 ± .6	0.1671 ± 32	28.10 ± .20
1400	182.6 ± .2	10.264 ± 20	4.463 ± 20	71.6 ± .6	0.1854 ± 26	28.06 ± .16
1600	31.58 ± 4	0.467 ± 4	0.211 ± 4	3.17 ± 4	0.0863 ± 22	29.23 ±2.92
Total	($^{40}Ar^*$=715)	(K=0.60)	(Cl=459)	(Ca=7.6)		30.43

Ge 20 0.1573 g J = .001205

T (°C)	$^{40}Ar_{tot}$	^{39}Ar	^{38}Ar	^{37}Ar	^{36}Ar	t (Ma)
750	364.4 ± .4	1.060 ± 10	0.996 ± 14	1.42 ± 6	0.9768 ± 116	149.26 ±6.58
900	55.36 ± .12	0.641 ± 6	0.295 ± 4	2.89 ±.12	0.1547 ± 24	33.31 ±2.34
1000	564.8 ± 1.4	33.066 ± 72	17.344 ± 76	125.6 ± 1.0	0.6013 ± 84	25.98 ±.18
1050	492.1 ± .4	33.381 ± 82	17.107 ± 68	125.9 ± .8	0.3470 ± 52	25.90 ±.12
1070	177.0 ± .2	12.359 ± 34	6.227 ± 28	46.4 ± .4	0.1302 ± 28	24.92 ±.16
1090	67.11 ± 8	3.795 ± 18	1.913 ± 14	14.6 ± .2	0.0803 ± 22	25.40 ±.38
1110	73.36 ± 6	4.364 ± 14	2.214 ± 12	17.0 ± .2	0.0764 ± 22	25.85 ±.32
1140	83.90 ± .10	4.830 ± 12	2.462 ± 14	18.4 ± .2	0.0862 ± 22	26.82 ±.30
1170	107.3 ± .2	6.229 ± 30	3.202 ± 18	22.9 ± .2	0.1089 ± 20	26.72 ±.24
1200	26.52 ± 4	0.873 ± 12	0.469 ± 20	3.37 ±.18	0.0524 ± 94	28.01 ±6.66
1250	45.05 ± 8	2.037 ± 14	1.040 ± 8	7.70 ±.14	0.0691 ± 28	26.82 ±.86
1600	182.1 ± .2	2.728 ± 14	1.475 ± 14	10.3 ± .2	0.5142 ± 54	24.60 ±1.26
Total	($^{40}Ar^*$=1326)	(K=1.24)	(Cl=1198)	(Ca=8.5)		27.20

but settle to nearly constant values for the remaining 95%. This constancy and the generally good agreement with microprobe Ca/K (Tab. 1) suggest that one-phased hornblendes were measured and not polyphase aggregates or hornblendes with submicroscopic inclusions of different amphiboles or phyllosilicates. These would result in irregular Ca/K spectra (HARRISON and FITZ GERALD, 1986; ONSTOTT and PEACOCK, 1987). One other bit of information made available by the stepwise heating results is that the Ca/Cl ratio (calculated from the $^{37}Ar/^{38}Ar$ ratio) is even more uniform than the Ca/K ratio. This regularity reinforces the hypothesis that all hornblendes are homogeneous. It must be concluded that the step-age variations displayed by all samples are due to varying amounts of excess Ar at locations from which it is released at different activation energies during the stepwise heating procedure.

Maximum ages for Ar retention in hornblende can be estimated by selecting the minima of the saddles. These are 28.96 ± .12 Ma for Siss 3, 30.59 ± .14 Ma 1, 29.38 ± .12 for Mer 1, 31.25 ± .22 for Sor 1, 25.71 ± .19 for Iorio 2, and 24.92 ± .16 for Ge 20. Integrated ages (Tab. 2) are always higher than these minimum ages, most dramatically in the case of Ma 1, Mer 1, and Iorio 2 by several Ma. From these integrated ages, which are comparable to conventional K–Ar ages, it must be concluded that K–Ar dating of single hornblendes, *may*, (but not always) yield wrong ages. The ^{39}Ar–^{40}Ar technique has the advantage to at least *identify* such disturbed ages. From the saddle minima two age groups are evident: 29–31.5 Ma for the eastern four hornblendes, and 25–26 Ma for the western two.

The use of mimimum saddle ages for the interpretation is not fully satisfactory as real ages may be lower because the actual amount of excess Ar remains unknown. Complementary information may be gained from the three-isotope (isochron) correlation diagram, $^{36}Ar/^{40}Ar$ versus $^{39}Ar/^{40}Ar$ (TURNER, 1971; PODOSEK et al., 1973). This diagram is preferred over the more traditional $^{40}Ar/^{36}Ar$ versus $^{39}Ar/^{40}Ar$ plot because the reference isotope is ^{40}Ar, which is more abundant than ^{36}Ar and therefore measured with greater precision. The y-intercept of this isochron yields the initial $^{36}Ar/^{40}Ar$ composition, while the x-intercept yields the $^{39}Ar/^{40}Ar$ ratio corresponding to the sample's age.

Several a priori conditions must be satisfied to deduce age-information from this diagram. (1) The used steps must contain significant amounts of Ar; (2) the Ca/K of the used steps must be constant and typical for the mineral studied; (3) the MSWD should be close to unity for large numbers of steps or lower for small numbers; (4) the used steps should be successive, as a "jumping" isochron is not supported because the degassing of reservoirs is believed to occur gradually, not episodically. The isochrons used in Fig. 3 were fitted in a way which optimizes all these conditions. In those cases where the conditions were fulfilled, a valid age was derived. Where one of the conditions is violated, the derived fit is called a "pseudoisochron" and the age is not rigorously meaningful. We observed that pseudoisochrons were very sensitive to addition of contiguous steps (the MSWD rose sharply, and/or the age changed significantly) while satisfactory isochrons were stabler in this respect, as long as MSWD ~ 1.

These requirements are fulfilled in sample Siss 3 only (Fig. 3a). The steps 4–11 fit statistically perfectly with MSWD = 0.5. Considerable excess Ar as testified by the y-intercept (corresponding to $^{40}Ar/^{36}Ar = 340$). The age is 28.59 ± .16 Ma. A satisfactory, though not perfect fit is obtained also for Mer 1 (Fig. 3c). Again, excess Ar is present and the isochron age is 28.80 ± .33 Ma for steps 7–10, indistinguishable from that of Siss 3. This approach fails in all other samples, as one or more of the above conditions are violated. For Ma 1, the steps 5–9 yield an "age" of 28.5 ± 2.4 Ma, but the large MSWD of 28.8 indicates that this isochron is statistically invalid. For Sor 1, the steps 6–12 yield an "age" of 31.5 ± 1.5 Ma. This is overlapping with the U–Pb zircon age of 31.9 Ma for the tonalite which would imply a closure temperature of > 700 °C for this hornblende – an unlikely case. In addition, the high MSWD of 7.8 indicates that the fit is, again, a pseudoisochron and that several different excess Ar-reservoirs are present. One possible explanation is that the $^{40}Ar_{excess}/K$ ratio is constant and the apparent spread on the isochron is produced by varying contributions of air-Ar. In this case inevitably an air-Ar intercept would result and the isochron age would be too high. The low ages for the western two samples are roughly confirmed, but in both cases the high MSWD values again suggest the presence of different Ar-reservoirs.

In summary plateau ages result from none of the samples, and the isochron approach fails in four out of six cases. However, the eastern four samples are *compatible* with a common age of 28.8 Ma. The western two are so irregular that it is impossible to decide unambigously whether the age difference (26 Ma for Iorio 2, 25 Ma for Ge 20) is significant or whether both samples should be assigned the same age, 25 Ma.

Excess Ar must also have been present in some of the hornblendes dated so far by K–Ar in the Bregaglia: DEUTSCH and STEIGER (1985) dated a tonalite hornblende from Bagni di Masino with 32 ± 1.2 Ma. This is coincidentally the intrusion age of the tonalite but about 3 Ma too old compared to the Siss 3 isochron age of 28.8 Ma. The same is the case for a 32.1 Ma age from the same locality by WIEDENBECK and BAUR (1986). Far in excess is an age of 36 Ma for an easterly hornblende (Val Preda rossa) by the same authors as is the 37 Ma age from a boulder hornblende by GIGER and HURFORD (1989). The interpretation of these ages as tonalite magma emplacement age is untenable. However, minimal K–Ar ages of 29.5–29.8 Ma for the central tonalite at Val Masino, Mello, and Livo (WIEDENBECK and BAUR, 1986) approach the cooling ages presented in this study.

4.3. BIOTITE K–Ar AGES

Biotite K–Ar ages are given in Tab. 3. Ages decrease very regularly from 26.4 in the east to 21.0 Ma in the west. Published biotite Rb–Sr ages from the Bregaglia tonalite are 21.8 ± 2.3 Ma in the Mera Valley very close to sample Mer 1 (JÄGER et al., 1967) and 21.8 ± 0.5 Ma (WIEDENBECK, 1985), and 23.5 ± 0.5 Ma at Mello, midway between Mer 1 and Ma 1 (WIEDENBECK, 1985). Published K–Ar ages are 21.9 ± 0.5 at the Mera Valley and 23.5 ± 0.5 at Mello (WIEDENBECK, 1985).

Tab. 3 Biotite K–Ar data. Errors are 2 sigma.

Sample	K [weight%]	$^{40}Ar_{rad}$ [pl/g]	%	t [Ma] ± 2 sigma
Siss 3 Bio	7.49	7744	74.9	26.4 ± .6
Ma 1 Bio	7.67	7782	77.6	25.9 ± .6
Mer 1 Bio	7.82	7249	71.3	23.7 ± .6
Sor 1 Bio	7.45	6543	67.6	22.5 ± .6
Iorio 2 Bio	7.40	6084	76.3	21.0 ± .6
Ge 20 Bio	7.94	6531	58.3	21.0 ± .6

5. Discussion

5.1. THE COOLING HISTORY OF THE EASTERNMOST LOCATION

The wealth of age determinations by different methods and the proximity of the granodiorite intrusion requires a separate discussion of the easternmost locality, Siss 3. One obvious geological implication concerns the cooling history derivable from the ages: Given a U–Pb intrusion age of 31.9 Ma for the tonalite and 30.1 Ma for the granodiorite (VON BLANCKENBURG, 1990), the hornblende age of 28.6 and the biotite age of 26.4 Ma are both far too young to reflect postmagmatic cooling alone. Examples for purely postmagmatic cooling rates can be obtained from the neighboring S-Adamello batholith, which intruded at shallow and thus unheated crustal levels. Zircon U–Pb ages (HANSMANN, 1986) are mostly overlapping with biotite K–Ar (DEL MORO et al., 1983) or display a difference of 2 Ma at the most, corresponding to cooling rates of 200 °C/Ma or faster. In contrast, the cooling rate is 90 °C/Ma in the eastern Bregaglia if one uses a solidus temperature of 680 °C for the 30.1 Ma granodiorite intrusion (the proximity of which to the tonalite sample Siss 3 allows both to be treated in a common cooling history), and if one assumes that both hornblende- and biotite ages are cooling ages (corresponding to closure temperatures of 550 °C and 330 °C respectively [Closure temperatures used by VON BLANCKENBURG et al., 1989 adjusted to cooling rates of 90 °C/Ma]). In any case the cooling rate does not depend critically on these two values; it approaches the value typical for pure regional metamorphism (30–50 °C/Ma) rather than pure postmagmatic cooling. Probably they reflect postmagmatic cooling superimposed on post-greenschist metamorphic cooling: in a deep seated intrusion heat dispersion from the solidified magma via the country rocks was sluggish. Further evidence for long lasting thermal activities at the easternmost location is given by metasomatic veins, which occur in a roof pendant consisting of dolomitic marble enclosed in tonalite very close to the locality Siss 3. BUCHER-NURMINEN (1981) determined temperatures of 560–430 °C for the formation of these veins and ascribed them to SiO_2 metasomatism during the cooling history of the intrusion. This prolonged postmagmatic activity, which is most probably intensified and delayed by the granodiorite intrusion only 2 km away, can now be dated at ca. 29–28 Ma.

The overall result is that the eastern Bregaglia tonalite was at temperatures sufficiently high to prevent Ar accumulation in hornblende for about 3 Ma. This conclusion is supported by reset U–Pb sphene and apatite ages from the eastern Bregaglia (VON BLANCKENBURG, 1990).

A cooling history typical for shallow intrusion is testified by boulders of the Bregaglia tonalite which were recovered from the southern Molasse basin (WAGNER et al., 1979; GIGER and HURFORD, 1989). Biotite K–Ar ages from the tonalite boulders buried as early as 31–28 Ma ago yield ages of 31.3–32.1 Ma (GIGER and HURFORD, 1989) – exactly the intrusion age of the tonalite. This means that the higher levels of the tonalite intruded at very shallow dephts, cooled very quickly, and were eroded and incorporated in the Molasse around 31–28 Ma bp (depending on the calibration of the Rupelian/Chattian boundary), very shortly after the granodiorite intrusion (30.1 Ma, VON BLANCKENBURG, 1990).

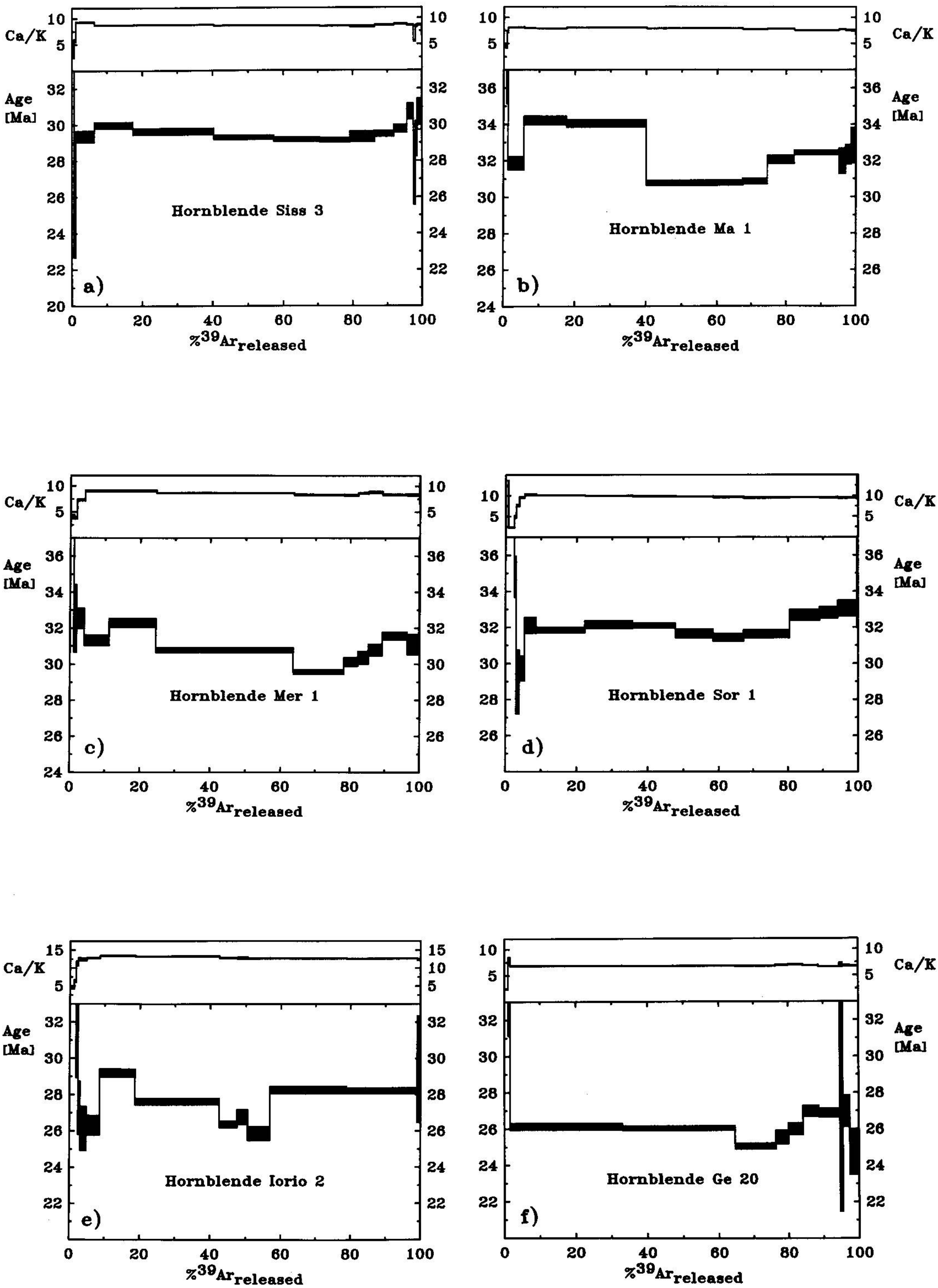

Fig. 2 Age- and Ca/K spectra. Errors are 2 sigma.

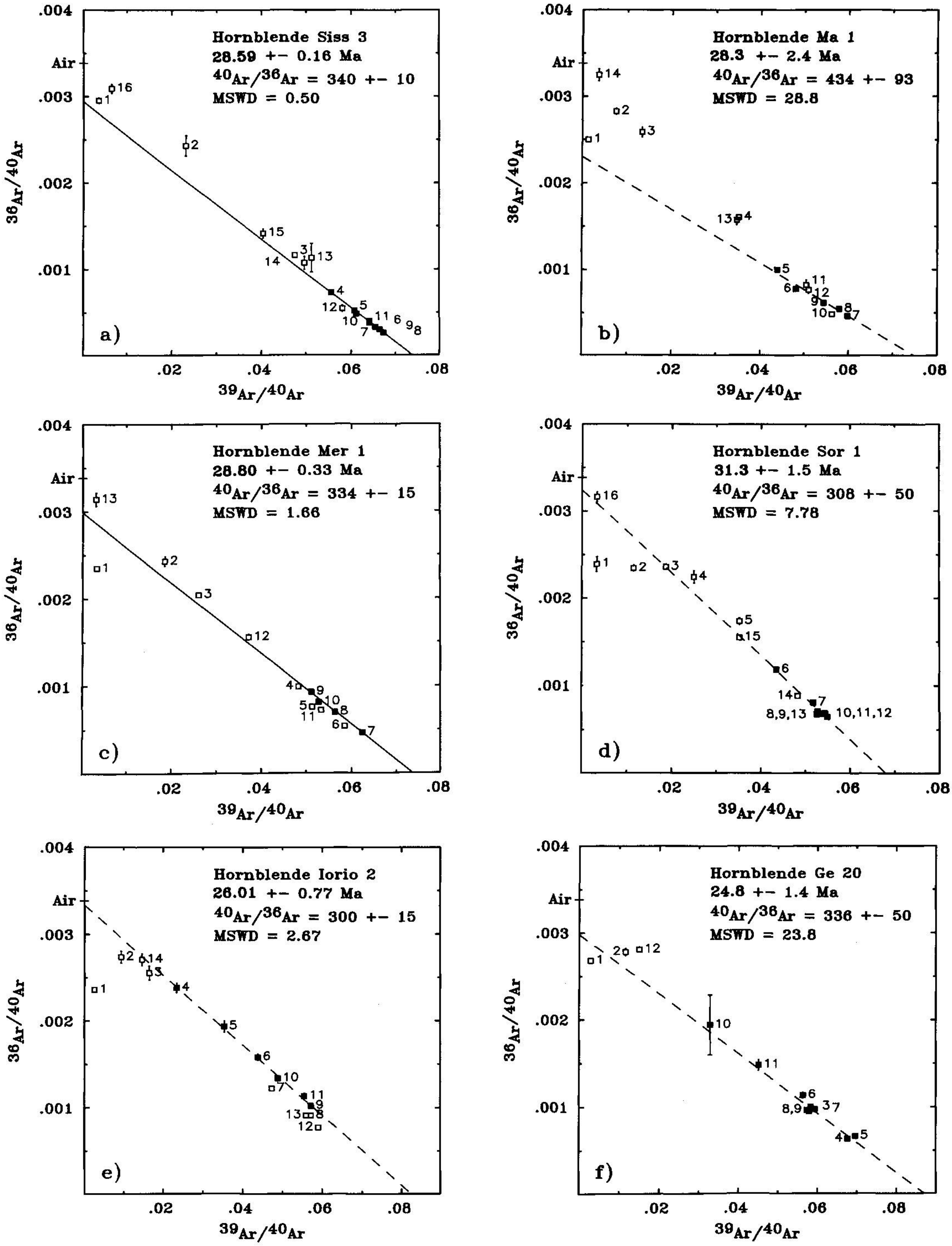

Fig. 3 Isochron plots. Errors are at the 95% confidence level. The steps marked with filled symbols were used for regression line calculation (York, 1969). Continuous lines indicate true isochrons, dashed lines indicate pseudoisochrons (see text). "Air" denotes atmospheric $^{40}Ar/^{36}Ar$ ratio.

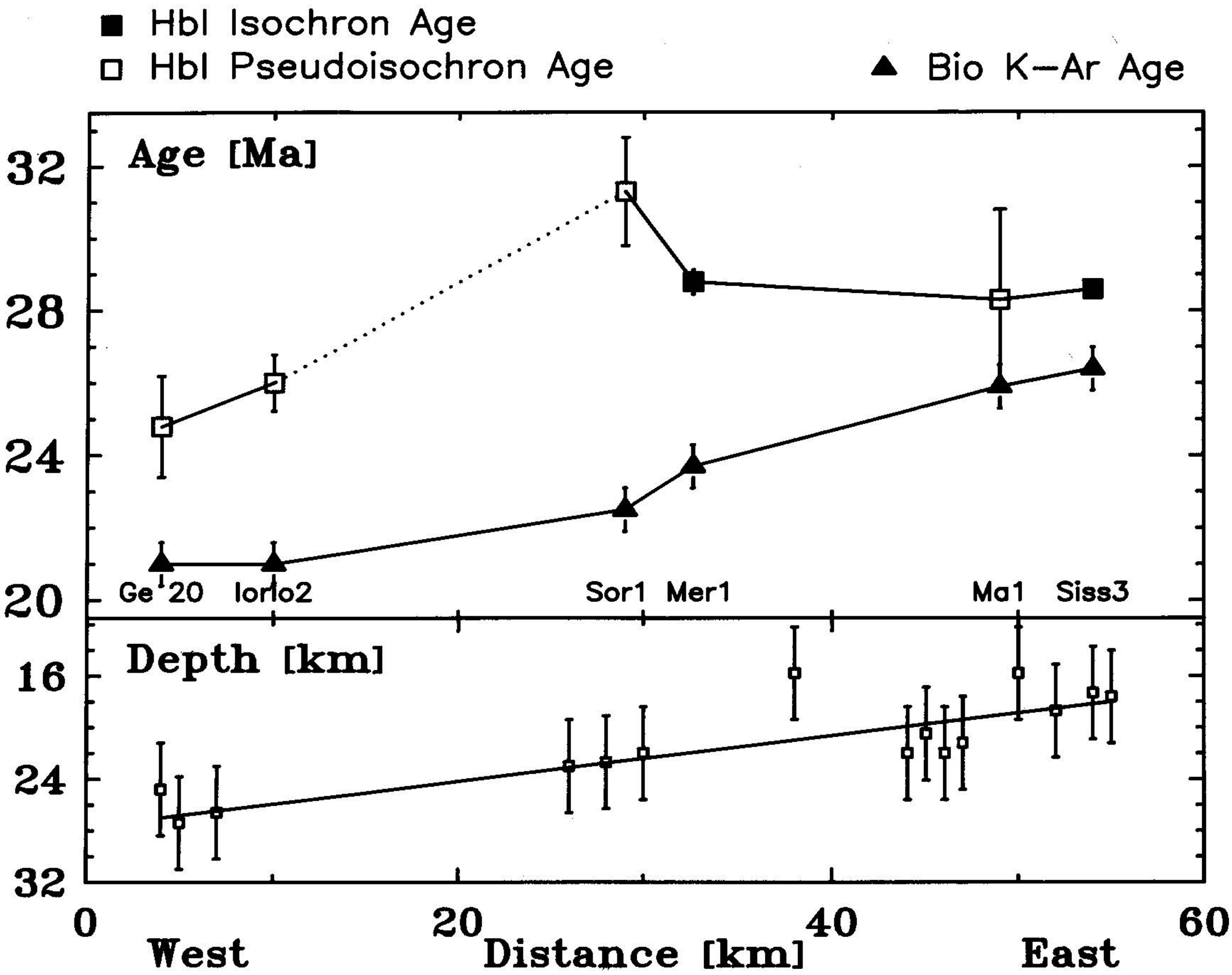

Fig. 4 Age and depth profile through the Bregaglia tonalite. The depth is from hornblende-barometry (REUSSER, 1987). The depth errors correspond to 1 kbar (HOLLISTER et al., 1987). Biotite and hornblende ages are 2 sigma. Into the latter an error of 0.3% was propagated to account for inter-sample flux uncertainties.

5.2. THE HORNBLENDE EAST-WEST TREND

Further conclusions based on the hornblende ages can only be tentative as the disturbed spectra should not be overinterpreted. An attractive and simple interpretation would be that the "real" hornblende ages decrease continuously from > 29 Ma in the east to ca. 24–25 in the west and that the humps in Fig. 4 are due to uncorrectable excess Ar. Parallel trends for biotites and hornblendes would be what one expects as result of the tilted uplift. The similarities of the statistically well legitimated ages of Siss 3 (28.6) and Mer 1 (28.8 Ma), located ca. 22 km apart (i.e. about one third of the total E–W extension of the tonalite) could be explained by the fact that in locality Siss 3 the thermal activity was prolonged owing to its proximity to the younger granodiorite intrusion. Basing on the six hornblende results, we can make some speculations (to be taken with extreme caution, as we explained above).

1) All hornblendes are metamorphic recrystallization ages. This is a contradiction to the opinion of REUSSER (1987) who determined that the crystallization temperatures of tonalite hornblendes lie within the melting interval.

2) The eastern group represents slow postmagmatic cooling, while the western group reflects post-regional metamorphic closure: the eastern tonalite intruded into moderately heated crust in which low heat conduction prevented fast cooling of the solidified magma, while the Iorio tonalite intruded into country rocks that were experiencing their regional metamorphic climax, and never cooled more than allowed by regional uplift. Temperature estimates for the mineral assemblages in the eastern country rocks prior to tonalite intrusion are greenschist-facies in the Malenco serpentinite

(TROMMSDORFF and EVANS, 1972), or up to 450 °C in the Margna nappe (GUNTLI and LINIGER, 1989). As for the western region, HEITZMANN (1975) reports occurrences of regional metamorphic sillimanite immediately to the north of Sorico implying temperatures of ca. 700 °C.

3) A similar scenario would be that the regional metamorphic temperature *maximum* occurred before the intrusion in the east, e.g. at 35–38 Ma (HURFORD et al., 1989) and the eastern hornblende ages are postmagmatic cooling ages. In the west, the regional metamorphic maximum occurred after the intrusion, e.g. at 23–29 Ma (DEUTSCH and STEIGER, 1985) and the western ages are cooling ages after this event. Such a diachronism of metamorphism at different tectonic levels was first postulated by thermal modelers (OXBURGH and ENGLAND, 1980).

4) The eastern ages are cooling ages, while the western ages reflect recrystallization due to movements along the Insubric line. Indeed, strong postintrusional deformation was observed by VOGLER and VOLL (1981). HEITZMANN (1987) and FISCH (1989) describe steeply northward plunging hornblende lineations in the strongly foliated Iorio tonalite and ascribe these to a steep backthrusting of the Central Alps over the southern Alps. The age of the strong uplift as derived from boulder deposition in the Molasse is 31–20 Ma (GIGER and HURFORD, 1989), which is in agreement with HURFORD (1986), who suggested an age between 23 Ma and the Bregaglia intrusion. However, the hypotheses that the hornblendes of the Iorio tonalite crystallized during this backthrusting event, contrasts with REUSSER's (1987) observations of magmatic chemistry and mineralogy for the tonalite and its hornblendes.

5) Closure temperatures may be very well variable in our samples due to individual microstructural complexities, such as dislocation density variations, which are not visible in the Ca/K spectrum (ONSTOTT et al., 1990). Therefore one should not necessarily expect a smooth cooling age trend.

It is difficult to find the correct answer to this multiple choice problem at the current state of knowledge. The least contradictory speculations appear in scenario (3), but matters are complicated by the results of thermal modeling of PTt-paths in extensional tectonic regimes (RUPELL et al., 1988): the shape of PT-paths is highly dependent on the style of deformation and may deviate considerably from linear geothermal gradients in *pure shear* environment. During *simple* shear, Tt-curves are modified as function of uplift rate. It is this finding which makes us hesitate to perform simple uplift rate calculations utilizing the arbitrary 30 °C/km gradient as done by HURFORD (1986). Such calculations may be justified under very simple circumstances, but are unlikely to be adequate to a thermally and tectonically active regime as the Central Alps close to the Insubric line.

5.3. THE BIOTITE EAST-WEST AGE TREND AND THE TIMING OF THE TILTING

The decrease in biotite ages from east to west correlates with depth estimates (Fig. 4, after REUSSER, 1987) and is indicative of the later uplift of the western Bregaglia due to eastward tilting (SCHMID et al., 1989). This pattern is enhanced by the fact that westward decreasing cooling ages can be followed through the whole Central Alps (WAGNER, 1977; SCHMID et al., 1989). In addition, the larger age difference between the intrusion age of the main units (assuming similar ages for the eastern and western tonalite) and the biotite ages in the west indicates that the cooling rates were slower, which is a result of the increasing postmetamorphic character of the cooling.

The end of the tilting of the Bregaglia body can be estimated from apatite fission track data (WAGNER et al., 1977). A rough correction of these ages for sampling elevation yields similar ages of ca. 13 Ma for all locations studied (e.g. E of the Mera valley). This implies that the intrusion was uplifted as a definitely tilted block through the apatite fission track closure isotherm at 13 Ma and was positioned as it is now. In contrast, SCHMID et al. (1989, Fig. 3) plotted uncorrected FT ages which implies a pseudo-E–W-trend.

6. Conclusions

We obtained six ^{39}Ar–^{40}Ar spectra on hornblende, and K–Ar ages on the coexisting biotites. The latter decrease from 26.4 in the east to 21 Ma in the west. These biotite ages are clearly cooling ages after a regional metamorphism which affected the intrusive body as a whole with temperatures which were at least sufficient to reset the Ar-system in biotite and the ages decrease is due to the tilted uplift of the intrusion.

Hornblendes dated with ^{39}Ar–^{40}Ar yield disturbed spectra with minima considerably younger than their integrated ages and published conventional K–Ar ages. Clearly excess-Ar is present in varying amounts (between 30 and 300 pl/g). The constant Ca/K ratios allow the conclusion that homogeneous hornblendes were dated free of submicroscopic exsolution and that the scatter in step ages is produced by degassing of different excess Ar reservoirs. None of the hornblendes displays a typical plateau but statistically significant isochron ages can be calculated for two out of six samples. These ages are 28.6 Ma for the easternmost sample and 28.8 Ma for a sample from the central Bregaglia, while the two western samples from the Iorio tonalite yield weakly constrained ages of 24–26 Ma.

Several scenarios can be envisaged for the decrease of hornblende ages from ~ 29 Ma in the east to ~ 25 Ma in the west. The most likely one is that the age of the metamorphic climax was younger in the deeper part of the intrusion in the west, and relatively older in the eastern, shallower level, probably even older than than the 30.1–31.9 Ma old intrusion itself. The vagaries associated with the ages, the possibility of a diachronous metamorphic climax and the nonregular fashion of PTt-paths in tectonically active regimes prohibit at this time quantitative conclusions regarding the cooling- and uplift history of the Bregaglia.

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