Zeitschrift: Schweizerische mineralogische und petrographische Mitteilungen = Bulletin suisse de minéralogie et pétrographie

Band: 69 (1989)

Heft: 3

Artikel: A revised thermal history for the Gran Paradiso massif

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DOI: https://doi.org/10.5169/seals-52797

SCHWEIZ. MINERAL. PETROGR. MITT. 69, 319–329, 1989

A revised thermal history for the Gran Paradiso massif

by *Anthony J. Hurford*[1] and *Johannes C. Hunziker*[2].

Abstract

Eight gneiss samples from the Pennine Gran Paradiso nappe, Western Alps, yielded K-Ar phengite ages of 116 and 53 Ma and biotite ages between 48-37 Ma, highly concordant fission track zircon ages of 30±1 Ma and fission track apatite ages between 20 and 24 Ma with an apparent normal gradient with respect to altitude. The sparse radiometric results available for the eo-Alpine period of the Gran Paradiso, when considered with data from the surrounding areas of the Western Alps, suggest a metamorphic peak at 80-110 Ma, with an overall eo-Alpine cooling rate of ≈7.5°C/Ma. The biotite and fission track data constrain the meso- and neo-Alpine time-temperature cooling path of the Gran Paradiso, indicating a monotonic slow cooling of the order of 10°C/Ma. Apatite confined track length distributions confirm slow-cooling since early Miocene times. This study does not support the hypothesis of an Eocene Himalayan-type inverted metamorphism of the Gran Paradiso area.

Keywords: Age determination, K-Ar method, fisson track, apatite, cooling path, Gran Paradiso massif.

1. Geological Background

The Gran Paradiso basement massif, lying on the borders of the French and Italian Alps some 40 km northwest of Turin, is comprised of metabasic and metasedimentary rocks, intruded by Hercynian granites. In Alpine times the entire sequence was overprinted during a Cretaceous high-pressure orogenesis, followed by a Tertiary greenschist facies metamorphism, resulting in high pressure relics in a greenschist surrounding (BERTRAND, 1968; CALLEGARI et al., 1969 DAL PIAZ and LOMBARDO, 1986; VEARNCOMBE, 1983). The Gran Paradiso, together with the Monte Rosa (BEARTH, 1952) and Dora Maira (VIALON, 1966) complexes represents the pre-Triassic basement of the Upper Penninic element within the Piemont Zone of the Western Alps. This pre-Triassic basement is unconformably overlain by Permo-Triassic quartzites and Triassic dolomitic limestones, and topped by discordant Jurassic and Cretaceous schistes lustrés with intercalated meta-ophiolites which represent the position of suture between the southern or Apulian and northern European plates (see DAL PIAZ and LOMBARDO, 1986). The Gran Paradiso basement is surrounded by the Piemont schistes lustrés nappe, in turn overlain in the east by the Austroalpine Sesia-Lanzo Zone and in the northwest by the Briançonnais-Vanoise basement (Fig. 1). The classical east-west profile across the Western Alps reveals a series of eastwards-plunging thrust masses; although for Monte Rosa an Alpine nappe structure is obvious, for Gran Paradiso and Dora Maira this becomes progressively less well-established, latest seismic data (BAYER et al., 1987) however confirming that the Gran Paradiso is also a nappe (Fig. 2).

The pre-Triassic and pregranitic rocks of the Gran Paradiso basement are predominantly metasediments with intercalated basic bands and boudins of presumed Lower Palaeozoic sillimanite grade metamorphism, together forming the *gneiss minuti*. This basement complex was intruded in Hercynian times by porphyritic granitoid rocks, the present-day Gran Paradiso augen gneiss. For the petrographically and structurally similar Monte Rosa granite, a Rb-Sr whole-rock isochron age of 320±20 Ma (1.42 $x10^{-11}/a$) con-

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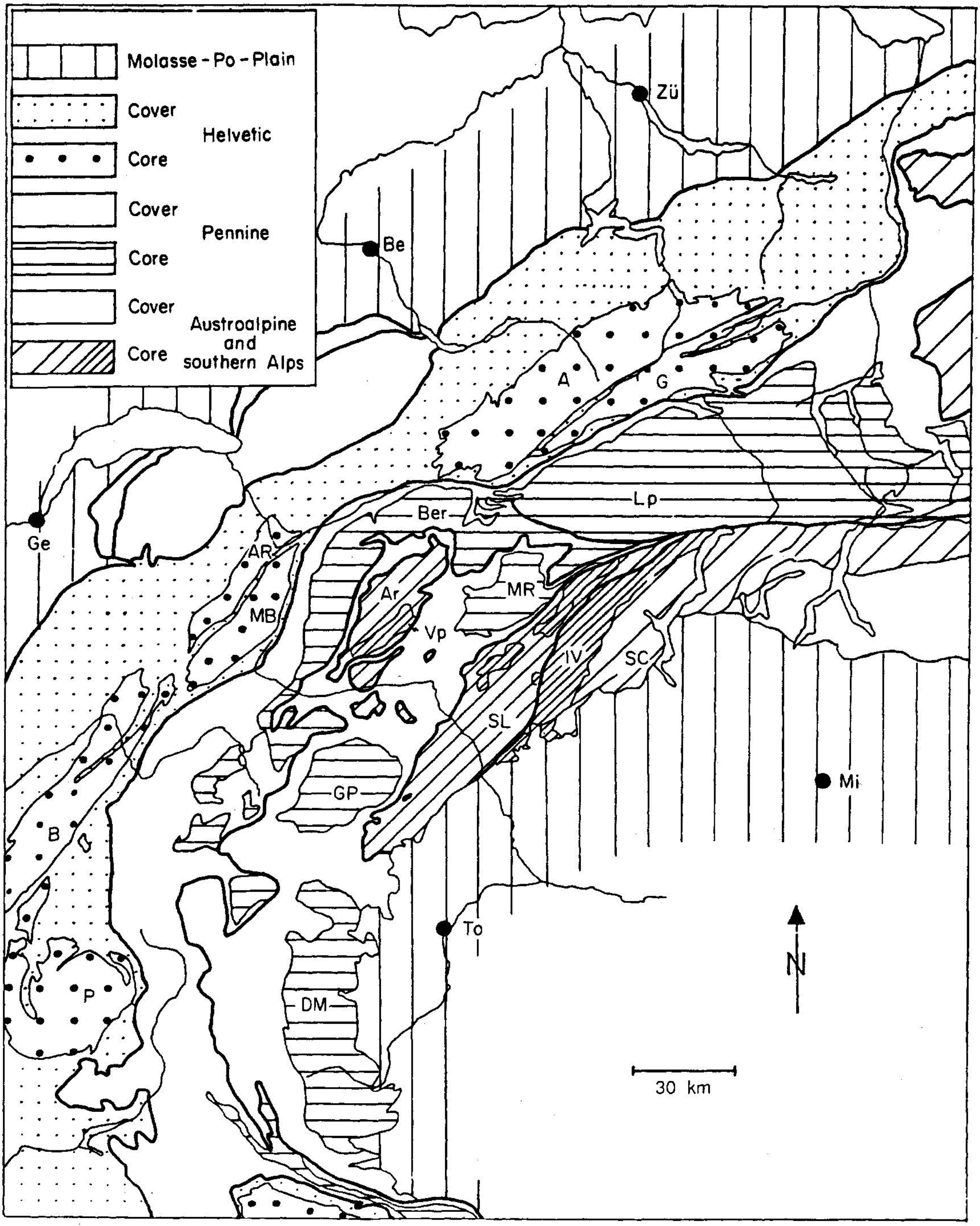

Fig. 1 Geological sketch map of the Central and Western Alps:
Abbreviations: A = Aar massif; Ar = Arolla Series; AR = Aiguilles Rouges massif; B = Belledonne massif; Be = Bern ; Ber = northern Bernhard nappe; C = Canavese zone; DM = Dora Maira massif; G = Gotthard massif; Ge = Geneva; GP = Gran Paradiso massif; IV = Ivrea-Verbano zone; Lp = Lepontine Alps; MB = Mont Blanc massif; Mi = Milan; MR = Monte Rosa massif; P = Pelvoux massif; SC = Strona-Ceneri zone; SL = Sesia-Lanzo zone; To = Turin; Vp = Valpelline nappe ; Zü = Zürich ; (from HUNZIKER 1986).

firms a Carboniferous intrusion age (FREY et al., 1976); this age is seemingly supported for the Gran Paradiso itself by total lead ages on zircon (CHESSEX et al., 1964 and refs. therein). However, in polymetamorphic terrains the interpretation of total lead measurements is today highly questionable (DELALOYE, 1979) and accordingly the zircon ages reported by CHESSEX et al. must be treated with caution. In Permo-Carboniferous times this whole Lower Palaeozoic basement unit was covered by deformed volcanics and volcaniclastic sediments which today comprise the Bonneval gneisses (BERTRAND, 1968), and the Money Complex a sedimentary sequence, surrounding and overlying the Erfaulet granite. All three show only an Alpine metamorphic overprint and exhibit affinities to the Furgg Formation of the Monte Rosa nappe (WETZEL, 1972).

The polyphase Alpine history of the Western Alps starts in the Cretaceous with an eo-Alpine high-pressure regional metamorphic phase. In contrast to the Sesia Zone, it is dominantly the basic rocks in the Gran Paradiso which today reveal high pressure parageneses, with a few exceptions like the Bonneval gneiss where SALIOT (1979) reported the paragenesis of jadeite + quartz, and CHOPIN (1981) has shown that specific pelitic compositions display high pressure paragenesis. However, where present in the Gran Paradiso phengites are normally found as 3T polytypes. VEARNCOMBE (1983) has identified a series of 5 deformational phases: deformations D1 and D2 are contemporaneous with the Cretaceous high pressure event, whilst the subsequent deformations D3 and D4 are synchronous with Tertiary greenschist conditions, and the minor crenulations of D5 presumably postdate greenschist conditions.

Few radiometric ages have been determined so far for the Gran Paradiso, with *no* Rb-Sr determinations and only a limited amount of conventional K-Ar and ^{40}Ar-^{39}Ar data available. This restricted argon data set, together with petrological arguments and comparisons with Monte Rosa and Dora Maira (GOFFÉ and CHOPIN, 1986; DESMONS and HUNZIKER, 1987) suggest an eo-Alpine metamorphic peak of 8-15 kbar at ~400-500°C timed at ~110-80 Ma, with cooling ages down to 60 Ma . (CHOPIN, 1979; CHOPIN and MALUSKI, 1980; DAL PIAZ and LOMBARDO, 1986). From other mica ages in and around the Gran Paradiso (BOCQUET et al., 1974; DELALOYE and DESMONS, 1976; CHOPIN and MALUSKI 1980) the greenschist overprint of the high pressure event may be placed in the interval 45-30 Ma BP.

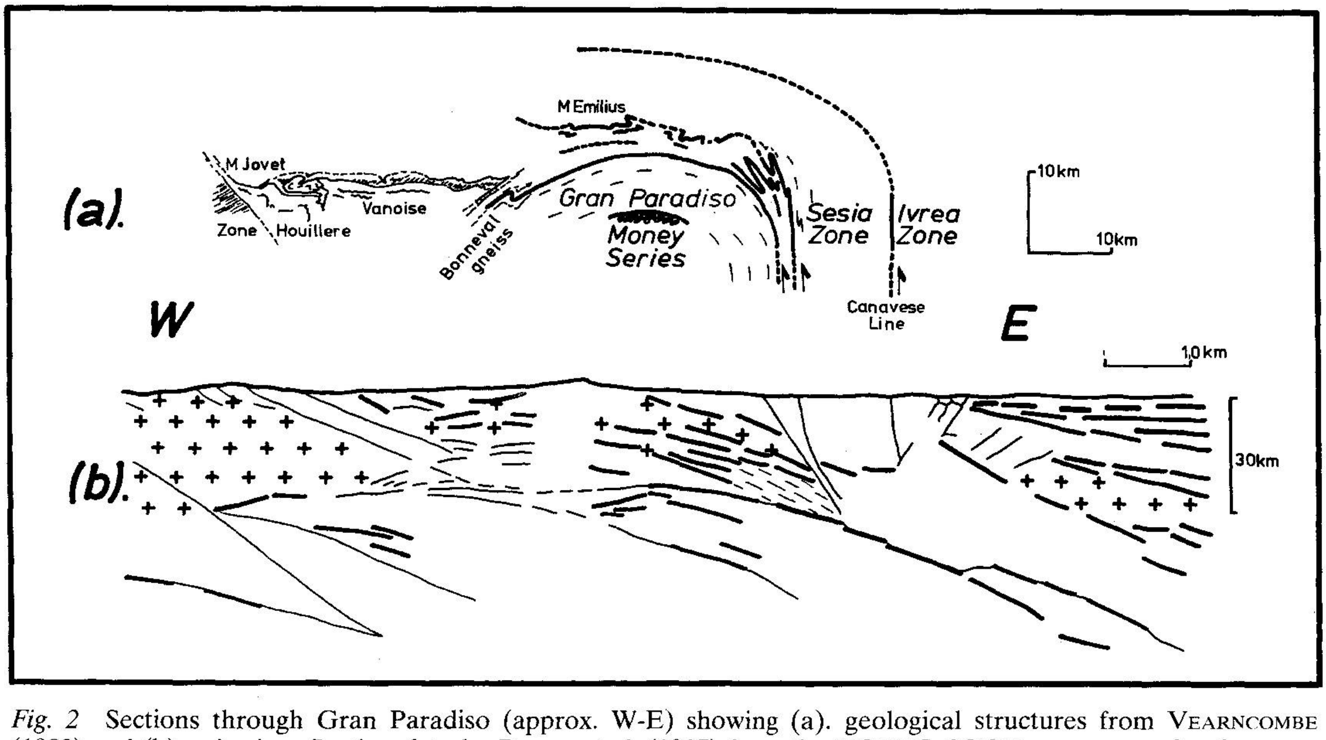

Fig. 2 Sections through Gran Paradiso (approx. W-E) showing (a). geological structures from VEARNCOMBE (1983) and (b). seismic reflection data by BAYER et al. (1987) from the ECORS-CROP programme for the same section.

2. Purpose of the present study

In a previous study on the Gran Paradiso massif, based upon 19 apatite and 35 zircon fission track analyses, CARPENA (1985) found a reversed gradient of age with altitude (see her results included for comparison in Fig. 4) which she interpreted as a nappe emplacement metamorphism: an inverted metamorphism during Eocene time caused by the overthrusting of the Gran Paradiso basement by the (hot) Dent Blanche nappe. Although such a model has been discussed for the Himalayas, previous suggestion that such a mechanism occurred in the Western Alps has been advanced (on a small scale only) by GOFFÉ and VELDE (1984) and thus evidence for such a large-scale (~50 km) mechanism derives *solely* from Carpena's fission track ages. Comparison of these fission track ages with argon data reveal a conflict with the widely accepted succession of mica and fission track closure temperatures *viz.* Rb-Sr muscovite > K-Ar muscovite > Rb-Sr biotite ≈ K-Ar biotite > FT zircon > FT apatite (see detailed discussion in HURFORD, 1986). Five of Carpena's apatite fission track ages (see fig. 4) approximate to, or exceed the single published ^{40}Ar-^{39}Ar biotite age (CHOPIN and MALUSKI, 1980); similarly the range of zircon fission track ages between 93 and 29 Ma coincide with, or significantly exceed published ^{40}Ar-^{39}Ar and conventional K-Ar white mica ages (see Fig. 9 of CHOPIN and MALUSKI, 1980). Similarly discrepant fission track zircon ages have been reported by Carpena: from the Monte Mucrone area of the Sesia-Lanzo Zone, her zircon fission track ages being substantially older than Rb-Sr and K-Ar white mica ages (CARPENA, 1984; HURFORD and HUNZIKER, 1985; OBERHÄNSLI et al., 1985). For ophiolites from the Piemont - Monte Viso zone, comprising pillow lavas and pillow breccias exhibiting eo-Alpine eclogite facies overprint, CARPENA and

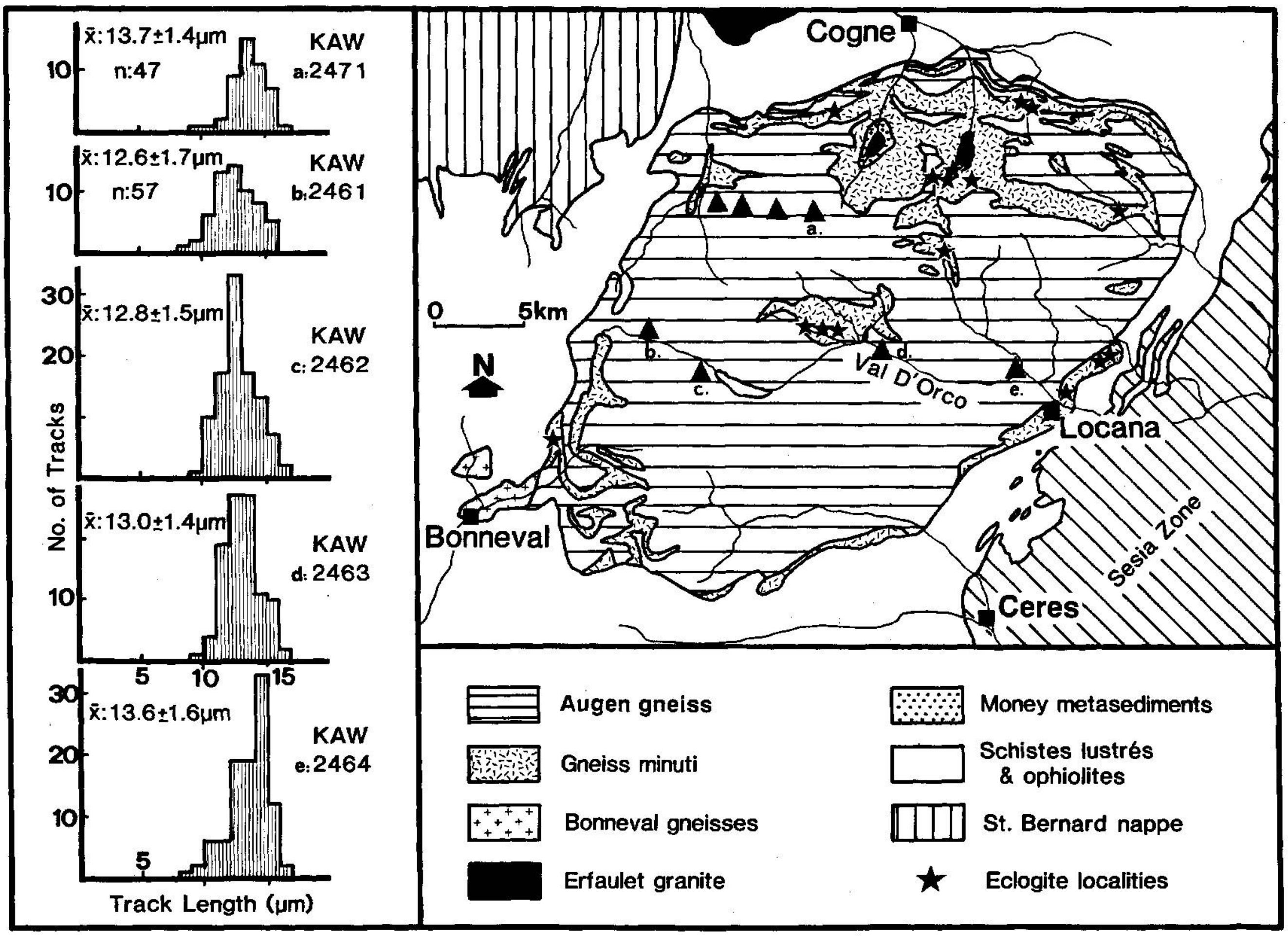

Fig. 3 Geological sketch map of Gran Paradiso (after COMPAGNONI et al., 1974 , showing sample sites (filled triangles) and measured apatite confined length distributions (100 tracks measured except where shown).

CABY (1984) presented Triassic zircon fission track ages interpreted as dating the time of premetamorphic emplacement.

Because of the important implications posed by Carpena's fission track data for the tectonothermal evolution of the Western Alps, a set of new gneiss samples from the Gran Paradiso was collected in an attempt to replicate her results, and to permit the analysis of both fission track *and* mica ages on the same rocks. Sampling localities are shown in Figure 3 and are detailed together with sample descriptions in the appendix.

3. Analytical Procedures

Using conventional rock-crushing, Wilfley-table, shaking-table, magnetic and heavy-liquid mineral separation techniques, zircon, apatite, biotite and white mica were separated, where present, from each of the Gran Paradiso samples. Fission track analyses utilised the techniques detailed in HURFORD (1986): all zircons together with apatites KAW 2471 and 2472 were dated using the *external detector method* (EDM); for other apatites the *population method* was employed. In addition, confined spontaneous track length distributions were measured for each apatite sample. Only well-etched prismatic apatite and zircon sections were selected for track counting and length measurement. Irradiations were performed in facility J1 of the HERALD reactor at Aldermaston, UK using uranium glasses SRM 612 and CN-1 as dosimeters (HURFORD and GREEN, 1983). Analytical data and calculated fission track ages are listed in Table 1 together with results from analysis of two zircon age standards from the Fish Canyon tuff (HURFORD and HAMMERSCHMIDT, 1985) and the Buluk Member tuff (HURFORD and WATKINS, 1987) included in the same irradiation. All fission track ages were calculated using the zeta calibration approach (HURFORD and GREEN, 1983), zeta values for the two dosimeter glasses being given in Table 1. For the K-Ar determinations, potassium was analysed in duplicate by flame photometry; argon was measured using a MM1200 mass spectrometer in static mode with an enriched ^{38}Ar spike (SCHUMACHER, 1975) calibrated against both known air volumes and standard minerals B-4M, B-4B, LP-6 and GL-O (FLISCH, 1982). Analytical data and calculated K-Ar ages are detailed in Table 2: all K-Ar ages were calculated using IUGS recommended constants (STEIGER and JÄGER, 1977).

Quoted analytical errors are 1s throughout: for fission track analyses they represent the conventional error of GREEN (1981), EDM analyses being subjected to the

χ^2-test (GALBRAITH, 1981) to detect whether the data sets contained any extra-Poissonian error. Errors on measured K-Ar ages were calculated according to the error propagation of Gaussian Law, combining individual uncertainties from potassium analysis, weighing, argon isotopic ratios and spike calibration.

4. Fission track and argon results and their implications

New analyses have provided 2 K-Ar phengite and 4 K-Ar biotite ages, as well as 8 fission track zircon and 6 apatite ages (Tables 1 and 2). The mica ages show the same spread as the data of CHOPIN and MALUSKI (1980) as well as those of BOCQUET et al. (1974) and DELALOYE and DESMONS (1976). The data also show internal consistency in that the measured ages are in agreement with the sequence of assumed closure temperatures (see above and HURFORD, 1986). The contrasting phengite ages of 116±1 and 53.4±0.8 Ma exceed the spread of ^{40}Ar-^{39}Ar total degassing white mica ages from 56 to 80 Ma for the Gran Paradiso reported by Chopin and Maluski, although in the Monte Rosa and Dora Maira massifs similar wider spreads have been reported (CHOPIN and MONIÉ, 1984; MONIÉ, 1985; GOFFÉ and CHOPIN, 1986). Our biotite K-Ar ages are more tightly grouped between 38 and 47 Ma, significantly older than the single total degassing age of 29.4±0.5 Ma reported by Chopin and Maluski for a sample with an imperfect degassing plateau from the same locality in the Orco Valley (Fig. 3). In general the more or less disturbed degassing patterns of Chopin and Maluski indicate the need for a critical evaluation of *all* K-Ar mica data measured for this massif. The singular absence of Rb-Sr data for the Gran Paradiso is currently being remedied (HUNZIKER, work in progress). Nevertheless, an eo-Alpine crystallisation phase and a possibly syntectonic Meso-Alpine crystallisation-recrystallisation are the most probable interpretation suggested by considering the combined data from Gran Paradiso, Monte Rosa and Dora Maira massifs.

Figure 4 presents a comparison of measured ages with sample altitude, also including the results found by Carpena for samples from the same localities. The K-Ar biotite results appear to reveal a correlation of increasing age with topographic altitude, although this is constrained by the results from only 4 samples. While such a relationship is fairly common for apatite fission

Tab. 1 Measured fission track ages and analytical data.

Sample and Elevation	Mineral	No. crystals	Spontaneous ρ_s	(N_s)	Induced ρ_i	(N_i)	$P\chi^2$% or $\bar{s}$'%	$\overline{\rho_s/\rho_i}$ $\pm 1\sigma$	Dosimeter ρ_d	(N_d)	Age Ma ($\pm 1\sigma$)
KAW 2471	zircon	20	70.86	(1466)	42.05	(870)	58%	-	3.203	(3835)	30.4±1.6
4060 m;	zircon	10	90.01	(908)	54.52	(550)	98%	-	3.202	(3835)	29.8±1.9
= JC 29	apatite	10	4.565	(44)	8.092	(78)	92%	-	2.555	(3123)	24.4±4.8
KAW 2472	zircon	20	80.89	(971)	46.57	(559)	29%	-	3.165	(3835)	31.0±1.9
3500 m	apatite	5	6.636	(97)	12.45	(182)	11%	-	2.551	(3123)	23.0±3.1
KAW 2473	zircon	20	98.95	(1352)	60.23	(823)	82%	-	3.120	(3835)	28.9±1.5
3030 m; = JC28											
KAW 2474	zircon	12	72.41	(860)	40.42	(480)	71%	-	3.105	(3835)	31.4±2.0
2530 m; = JC27											
KAW 2461	zircon	20	61.42	(1357)	39.06	(863)	10%	-	3.325	(3835)	29.5±1.6
1840 m;	apatite	250/200	2.655	(472)	18.75	(2667)	5%	-	5.008	(5950)	23.9±2.4
= JC22											
KAW 2462	zircon	20	58.39	(1111)	36.11	(687)	65%	-	3.290	(3835)	30.0±1.7
1620 m;	apatite	250/200	4.422	(786)	31.08	(2947)	7%	-	5.008	(5950)	23.9±1.8
= JC20											
KAW 2463	zircon	20	79.63	(1027)	48.77	(629)	79%	-	3.260	(3835)	30.0±1.8
1040 m;	apatite	250/200	5.507	(979)	46.48	(4407)	4%	-	5.008	(5950)	20.1±1.2
= JC13											
KAW 2464	zircon	20	86.52	(2033)	52.99	(1245)	<2%	1.671±0.097	3.227	(3835)	30.4±1.8
750 m;	zircon	10	79.27	(1407)	47.89	(850)	92%	-	3.227	(3835)	30.2±1.6
= JC11	apatite	250/200	2.107	(666)	17.56	(2497)	3%	-	5.008	(5950)	20.4±1.1
Fish Canyon Tuff	zircon	20	66.36	(3220)	45.50	(2232)	21%	-	3.395	(3835)	27.6±1.1
Buluk Member Tuff	zircon	20	9.852	(970)	11.61	(1143)	70%	-	3.355	(3835)	16.1±0.8

Notes:

(i). track densities (ρ) are as measured and are ($\times 10^5$ tr cm^{-2}); numbers of tracks counted (N) shown in brackets;
(ii). most apatite analysis by population method; apatites 2471 & 2472 and all zircon analyses by external detector method using 0.5 for the $4\pi/2\pi$ geometry correction factor.
(iii). apatite age calculated using dosimeter glass SRM 612 and zeta-612 = 339; zircon ages calculated using dosimeter glass CN-1 and zeta-CN-1 = 113 (Hurford and Green, 1983).
(iv). $P(\chi^2)$ is probability of obtaining χ^2 value ≥ observed value, for v degrees of freedom (where v = no. crystals - 1); mean ρ_s/ρ_i ratio used to calculate age and uncertainty where $P(\chi^2)<5\%$.
(v). for apatite population method analyses, relative standard error of mean track count ($\bar{s}$') is shown.
(vi). independent ages: Fish Canyon Tuff = 27.8±0.5 (HURFORD & HAMMERSCMIDT 1985) and Buluk Member Tuff = 16.2±0.2 Ma (HURFORD & WATKINS 1987).

Tab 2 Measured K-Ar ages and analytical data. (Note: all ages calculated using IUGS recommended constants).

Sample	Mineral and Fraction	K%	$^{40}Ar_{rad}$ (x10^{-6}) cm^3 (STP) /g	%$^{40}Ar_{rad}$	Age (Ma) (±1σ)
KAW 2461	phengite 60/80	8.88	18.72	96.04	53.4±0.8
KAW 2462	biotite 90/130	7.08	10.52	97.88	37.8±0.5
KAW 2463	biotite 60/80	7.34	11.31	93.65	39.2±0.5
KAW 2464	phengite 60/80	9.02	41.99	95.67	116±1
KAW 2472	biotite 100/130	7.01	12.89	99.25	46.8±0.6
KAW 2474	biotite >100	7.41	12.46	92.59	42.8±0.5

track ages (WAGNER et al., 1979), for micas it has so far not been reported anywhere in the Alps. However the observed age pattern could also be explained by the difference in horizontal distance of different samples from the Pennine-Austroalpine boundary, the Viu-Locana Line, and the pronounced differential uplift of the Gran Paradiso / Monte Rosa massifs along this line with respect to the Austroalpine Sesia-Lanzo Zone. For samples along this line, K-Ar and Rb-Sr biotite and fission track zircon systems yield ages of ~30 Ma, contemporaneous with the post-metamorphic calc-alkali magmatism of Biella and Traversella and trachy-andesitic dykes and flows (see SCHEURING et al., 1974 and refs. therein and CHOPIN and MALUSKI, 1980).

Within the Gran Paradiso massif, our measured fission track zircon ages are uniform, with a mean value of 30±1 Ma (1σ) irrespective of sample altitude and east-west position. Such a uniform age is indicative of a homogeneous uplift of the entire Gran Paradiso unit during mid to late Oligocene times. However, as Figure 4 shows, these results conflict totally with the zircon fission track data reported by Carpena, whose individual ages ranged from 93.10±2.31 to 29.08±1.54 Ma (2σ) and were inverted with respect to altitude. Note that although our data set is based on 8 samples compared to the 35 zircon analyses of Carpena, our samples were strategically collected with respect to altitude and all taken from identical, or very similar, locations to those cited by Carpena. The errors reported by Carpena for the zircon external detector method analyses utilised the formalism of JOHNSON et al. (1979), an approach questioned by both GREEN (1981) and GALBRAITH (1981), and subsequently abandoned. A more realistic error assessment by Poissonian statistics of, for example, Carpena's zircon analysis #1 gives an error of ±5.6 Ma at 2σ (*excluding* an uncertainty component from neutron dosimetry, usually ~3%) compared with the quoted 2σ error of ±1.54 Ma. Nevertheless, these differences in error assessment do not explain the discrepancies.

The fission track apatite data show a slight normal increase of age with altitude (Fig. 4) ranging from 20.4±1.1 for the lowest sample to

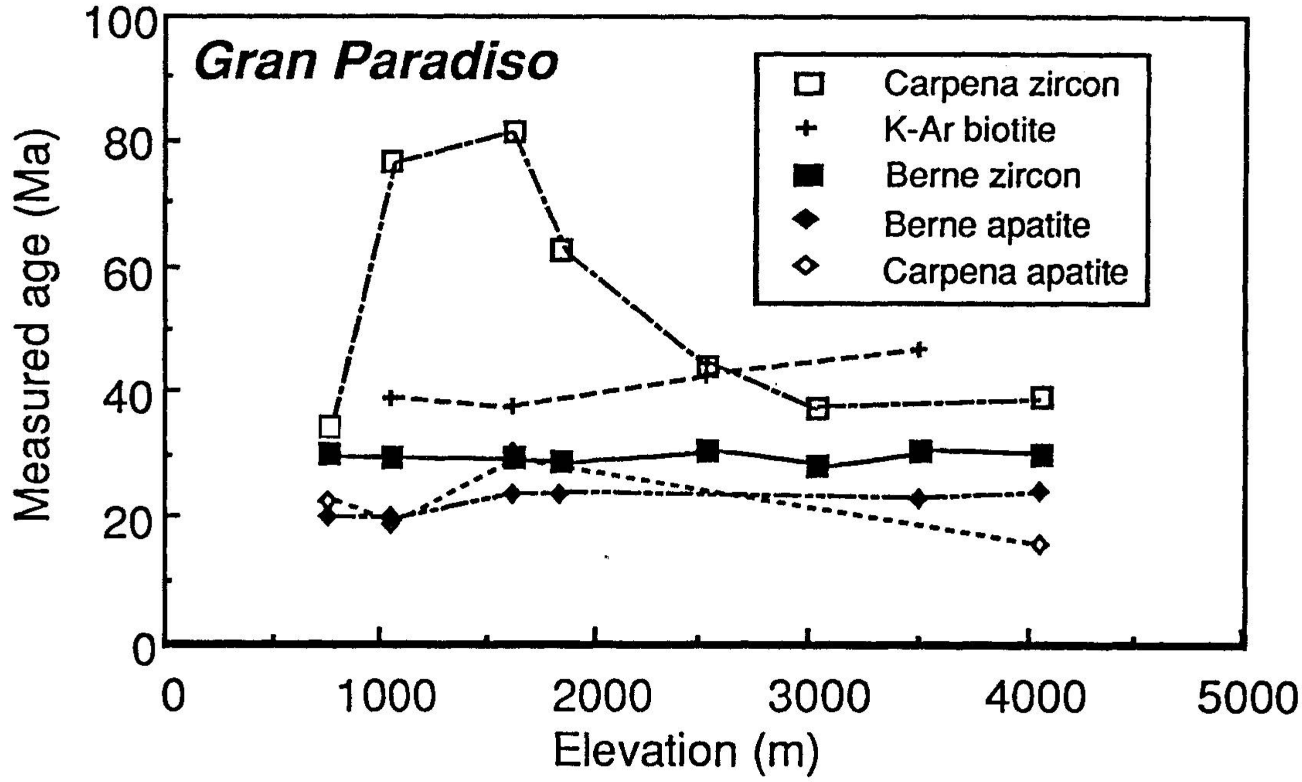

Fig. 4 Plot of measured K-Ar biotite and fission track ages vs elevation, including those data points measured by Carpena for samples from the same localities.

24.4±4.8 Ma for the summit sample - actually ages similar within analytical error. In her study, Carpena found that the measured (natural state) apatite ages spread between 15.06±3.09 and 41.52±9.07 Ma. Unfortunately, only 4 of her samples which yielded apatite fission track ages came from localities common to both studies, those from the two samples at lowest altitude giving ages similar to those found in this study, the higher samples yielding ages slightly discrepant (Fig. 4). The divergence of the apatite and zircon results reported by Carpena from those found in this study is at present inexplicable. Extensive control of system calibration against age standards has been made in Berne and reported in HURFORD and GREEN (1983); subsequent checks have been made, as shown for example in Table 1, by the analysis of age standards included with Gran Paradiso samples in the irradiation Bern-32. Subsequently Carpena, too, has reported analyses of the Fish Canyon apatite and zircon age standards (CARPENA and MAILHÉ, 1987), although not explicitly for those irradiations containing the Gran Paradiso samples. The problem cannot be explained by a systematic difference in calibration alone, since the patterns of ages with altitude in the two studies differ, as described above and shown in Figure 4. Although the problem at present remains unresolved, from our detailed control of system calibration, the concordant results from our repeat analyses of the highest and lowest zircons (see Table 1), the consistency of argon and fission track ages and regional similarity of results with other areas of the Western Alps, we are confident in using our results to formulate a revised thermal history for the Gran Paradiso massif, which contrasts with the inverted metamorphic zoning described by Carpena.

Combination of all the available radiometric information into a single time-temperature plot (Fig. 5) reveals for the meso- to neo-Alpine period a fairly tightly constrained cooling path with an overall rate between 40 and 20 Ma of ~15°C/Ma. Assuming a constant and normal geothermal gradient of 30°C/km this equates with an uplift rate of 0.5 mm/a. Below 20 Ma, apatite confined spontaneous track lengths i.e. tracks from the interiour of the crystal (Fig. 3) provide specific indicators of rates of cooling and uplift in the Gran Paradiso: measured mean lengths and distributions are typical of an undisturbed basement with a simple, monotonic cooling history (see GLEADOW et al., 1986), confirming that the samples

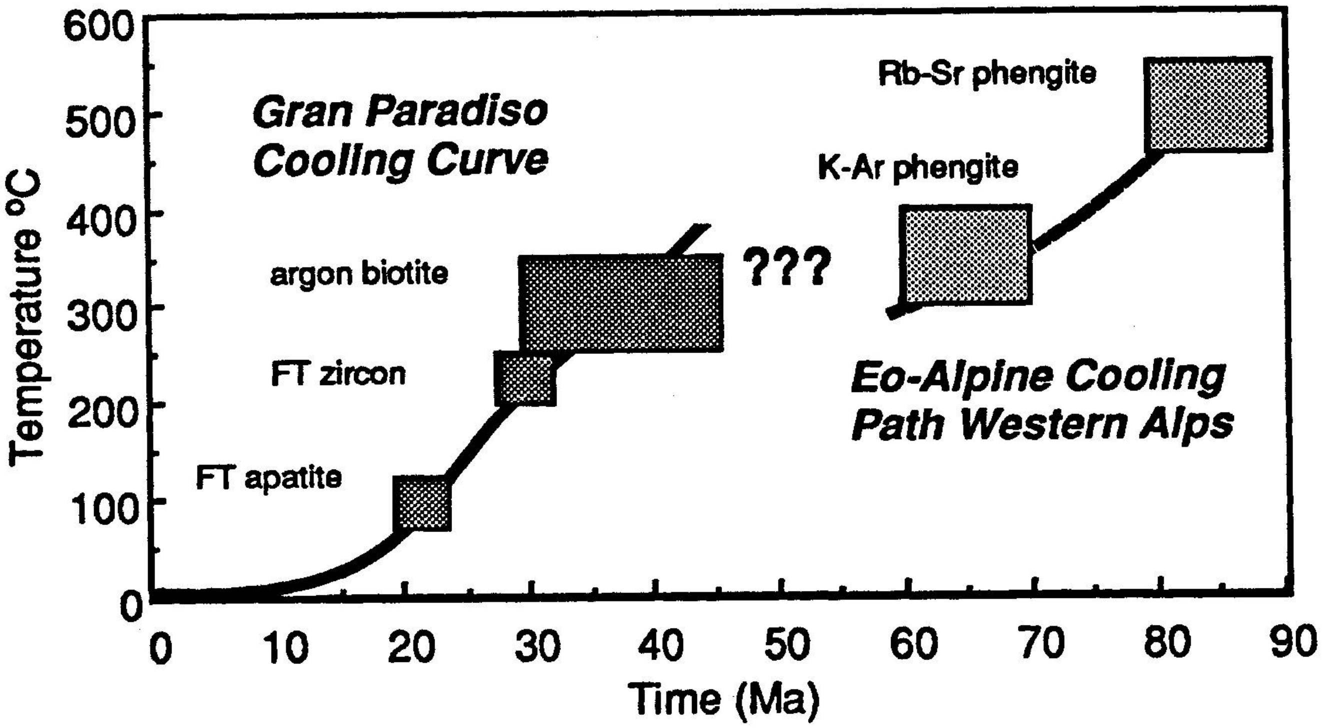

Fig. 5 Postulated Alpine time-temperature path for the Gran Paradiso massif, emphasising the remaining uncertainties in our knowledge for the early Tertiary thermotectonic evolution.

have neither cooled very rapidly (as in a volcanic sample), nor resided for long at temperatures which would cause significant track annealing. Assuming a normal geothermal gradient, depending on sample choice, rates of between ~0.3 and 1 mm/a may be concluded for the post-Oligocene uplift of the Gran Paradiso (Fig. 5). Further, the differences in apatite fission track ages at different altitudes permit direct calculation of an uplift rate of up to ~0.8 mm/a for the Gran Paradiso since the early Miocene, assuming that cooling is uplift controlled and that geotherms remained stationary and horizontal with regard to the uplifting massif (PARRISH 1983).

However, the totally different metamorphic regimes operative during eo- and meso-Alpine times indicate a distinct change in geothermal gradient. In eo-Alpine times eclogite facies conditions ranging between 8 kbar at 400°C and 30 kbar at 750°C (deduced from accepted PT conditions throughout the Western Alps, demand a geothermal gradient of the order of 5-10°C/km. Present-day estimates of geothermal gradient from lake sediment measurements (LANZA, personal communication) reveal normal values. The most likely time interval for the increase in the gradient lies at the change of metamorphic facies – from high-pressure eclogite to Barrovian-style greenschist in the internal Western Alps. In the external Briançonnais, this anomalously low geothermal gradient survived in part until meso-Alpine times as evidenced by the carpholite paragenesis throughout the internal parts of the Briançonnais unit (GOFFÉ and CHOPIN 1986).

5. Conclusions

Ages for different minerals and methods derived in this study are self-consistent with respect to assumed system closure temperatures. Individual fission track results and patterns of ages reported here are significantly different from those reported by CARPENA (1985) for the Gran Paradiso. We conclude that our radiometric dating studies furnish no additional evidence to support the hypothesis that the Gran Paradiso has been subjected to an inverted metamorphism in Eocene times as a consequence of overthrusting of the Dent Blanche nappe.

Definition of the eo-Alpine history, responsible for the remnant high-pressure mineral assemblages found in the Gran Paradiso basement rocks, is imprecise: by analogy with other areas of the Western Alps the metamorphic peak may be placed in the interval 80-110 Ma, white mica cooling ages suggesting cooling rates of ≈7.5°C/Ma. From metamorphic conditions during eo-Alpine times, geothermal gradients between 5 and 10°C/km can be deduced which, combined with cooling rates, permits calculation of exhumation rates of the order of 1 mm/a. New fission track zircon and apatite, and K-Ar mica dating analyses reveal a subsequent normal slow cooling at ~10°C/Ma for the Gran Paradiso massif during meso- and neo-Alpine times. During this time period metamorphic conditions indicate normal geothermal gradients of the order of 30°C/km, resulting in exhumation rates of ~0.3 mm/a.

Acknowledgements

This work was supported by Project No. 4.902.0.85.20 of the Schweizerischer Nationalfonds, which is part of the National Research Programme NFP 20 «Deep Structure of Switzerland». We are grateful to colleagues Andreas Bürgi, Reto Caluori, Andy Gleadow and Urs Klötzli and for assistance with sampling; and André Zingg, Chuck Naeser and Roland Oberhänsli for commenting on an earlier version of the manuscript. The analyses were made in Berne supported by a Swiss National Science Foundation grant to Emilie Jäger. Constructive reviews of B. Lombardo and F. Oberli are kindly aknowledged.

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Manuscript received July 12, 1989; revised manuscript accepted October 30, 1989.

Appendix 1: Sample locations, elevations and descriptions.

KAW 2461: Orco Valley, Chiapili; road from Locana to Col del Nivole; small road cliff; 1840 m; Gran Paradiso augen gneiss.

KAW 2462: Villa, Orco Valley; 10 m cliff beside stream inlet into lake; 1620 m; Gran paradiso augen gneiss.

KAW 2463: East of Noasca, south of stream; 1040 m; Gran Paradiso augen gneiss.

KAW 2464: small roadcut west of Bottegotto; 750m ; mylonitised Gran Paradiso augen gneiss.

KAW 2471: Gran Paradiso summit; 4060 m; augen gneiss.

KAW 2472: Gran Paradiso glacier, 1 km WSW of summit, cliff beside track to Ref. V. Emanuele; 3500 m; mylonitic 2 - micaaugengneiss

KAW 2473: Gran Paradiso glacier, 2 km W of summit, cliff beside track; 3030 m; mylonitic 2-mica augengneiss

KAW 2474: north of track from Ref. V. Emanuale to Pont, 3.7 km WSW of summit, cliff in Val Savaranche; 2530 m; mylonitic 2-mica augen gneiss.