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COOLING AGES DERIVED BY APATITE FISSION-TRACK, MICA Rb-Sr AND K-Ar DATING: THE UPLIFT AND COOLING HISTORY OF THE CENTRAL ALPS

(with 9 figures, 3 tables and 2 plates)

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I. INTRODUCTION

It is the intention of this paper to analyze the uplift history of the Central Alps by using radiometric age data. This approach is based on the fact that different radiometric clocks are turned on at different temperatures (« blocking temperatures ») during cooling or — in other words — that the ages are « cooling ages ». When cooling is essentially controlled by uplift and erosion, the cooling ages offer a unique opportunity to study the temporal and regional uplift behavior. Uplift rates are therefore proportional to cooling rates according to the equation

$$\text{uplift rates} = \frac{\text{cooling rates}}{\text{geothermal gradient}}$$

The Central Alps are especially suited for such a study because of the intensive geochronological investigations that have been conducted and the fast and differentiated uplift of the region. Most previous papers have discussed only single blocking temperatures for terrains of regional metamorphism. PURDY and JÄGER (in press) have compiled Rb-Sr and K-Ar white mica and biotite data; ARMSTRONG *et al.* (1966) had previously compared the biotite K-Ar and Rb-Sr results. This paper combines previously reported mica Rb-Sr, mica K-Ar, monazite U-Pb and apatite fission-track ages. The cooling temperatures dated with these different radiometric clocks in the Central Alps are: 530°C for monazite U-Pb; 500°C for muscovite and phengite Rb-Sr; 350°C for muscovite and phengite K-Ar; 300°C for biotite Rb-Sr and biotite K-Ar; and 120°C for apatite fission-track ages. The different blocking temperatures have been derived by different methods: for apatite fission-track ages by annealing experiments and, more recently, by dating samples from bore-holes; for Rb-Sr systems by comparing mica ages to metamorphic isograds; for K-Ar systems in micas by relating to Rb-Sr data; for U-Pb monazite ages by comparing the Rb-Sr and K-Ar systems, supported by independent $^{18}O/^{16}O$ evidence. The derivations of these temperatures are discussed in more detail in section II. The synthesis presented in this paper should not only give detailed information on the cooling history for the different regions of the Central Alps but it should also provide a check of the different blocking temperatures in relation to each other.

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In addition to the approach outlined above, uplift rates can be directly calculated from the apatite fission-track ages. The observed age increases with topographic elevation and reflects the time samples at different altitudes succesively passed the temperatures critical for track stability. This approach does not require knowledge of the blocking temperature and the geothermal gradient. It gives an independent check on the uplift rates derived from different radiometric ages.

II. ANALYTICAL METHODS AND RESULTS

1) Fission-track measurements on apatites

a) Experimental

The fission-track dating was carried out on concentrates of apatite crystals separated from the crushed and ground rock samples by using a shaking table, heavy liquids, and a magnetic separator. The size of the apatite crystals ranged between 50 and 150 μm. About 10 - 100 mg of apatite (which corresponds to several thousand grains) is sufficient for fission-track dating. For rock samples with low apatite content, the age measurement was carried out on only several hundred single grains. During the separation procedure, any heating was avoided which could result in track fading. A split of each sample was irradiated with thermal neutrons. The thermal fluences (ranging from 3.84 to 6.27×10^{14} neutrons/cm^2) were calibrated with copper monitors and standard glasses. The unirradiated and irradiated apatites were mounted in cold-setting epoxy, polished, etched, and counted under the same conditions in order to reduce systematic errors. Etching was with 5% nitric acid at 20°C for 45 seconds; counting was with oil immersion at 2500× magnification. The entire procedure is described in more detail by Wagner (1969). The ages were calculated with the decay constant $\lambda_f = 8.46 \times 10^{-17} y^{-1}$ (Galliker *et al.*, 1970; Wagner *et al.*, 1975).

b) Results

The apatite fission-track ages (including those reported previously by Wagner and Reimer (1972)) of the Central Alps range from 2.2 to 17.4 m.y. (Table 1). From these ages several regularities are noticeable. There is a clear correlation between the apatite fission-track ages and the topographic altitude of the sampling location. The ages increase with the altitude. This correlation can be observed for all regions (Figure 1) in which samples with sufficiently large altitude differences exist.

The apatite fission-track ages show a distinct regional distribution (Map 1). Because of the change of the apatite fission-track ages with topographic altitude, the ages were reduced to the same altitude level (1000 m) for the presentation in Map 1. For the reduction, the age vs. altitude curves of the corresponding regions were used (Figure 1). The sample locations which changed their color by this reduction process

TABLE 1 — Apatite Fission Track Ages and Alpine Biotite Rb-Sr Ages of Rock Samples from the Central Alps.

Sample N°	Locality	Coordinates	Elevation in meters above sea-level	Alpine Biotite Rb-Sr Ages in M.y.	Apatite Fission-Track Age (*) in M.y.
KAW 4	Brione	703750/128250	800	16.8±0.5	7.1
KAW 6	Lavertezzo	707900/124050	530	17.3±2.5	6.7
KAW 65	Tennmatte/Lötschental	627850/140150	1460		3.5
KAW 75	Claro	721925/125175	310	16.8±1.1	6.4
KAW 76	Castione	723850/121000	260	18.4±1.3	6.9
KAW 80	Camponi/Toce	676400/ 89700	210		14.2
KAW 82	Croppo/Toce	667600/107100	270	18.7±0.6	4.8
KAW 85	Teglia	674450/ 93100	210		10.8
KAW 87	Str. Erstfeld - Bocki	690750/187825	760		8.0
KAW 90	Malojapass	773600/141950	1800		15.0
KAW 91	Lago Campliccioli	649450/109955	1280		7.4
KAW 96	Oberwald - Gletsch	670695/155660	1610	13.2±4.2	4.8
KAW 101	Alpe al Lago/Isorno	672350/114700	830		6.7
KAW 102	Naviledo/Isorno	669670/112160	400		5.3
KAW 105	Truzzo	784600/134550	590	24.4±1.0	10.2
KAW 132	Novate/Mezzolo	755520/121280	310	17.7±1.0	11.2
KAW 137	Osogna	719690/129410	300	17.6±1.9	6.0
KAW 138	Pollegio	715570/135400	300	16.1±0.9	5.9
KAW 140	Chiggiogna	707030/145870	700	15.9±0.7	4.6
KAW 145	Soazza	735850/133020	580	18.4±1.6	6.4
KAW 159	Gondo	653960/116300	860	11.4±1.3	2.6
KAW 160	Alte Kaserne/Simplon	650400/115200	1160	11.0±1.1	2.5
KAW 161	Gabi/Simplonstr.	649580/115170	1200	11.0±1.0	2.6
KAW 164	Eisten/Simplon	647060/127550	1410	11.7±1.8	4.2
KAW 165	Eisten/Simplon	646540/127540	1390		4.4
KAW 168	Krummenalp/Lötschental	623200/138950	2020		4.6
KAW 189	Soazza	737630/137470	620	18.4±2.7	7.1
KAW 201	Verampio/Toce	668850/121600	520	13.4±0.5	2.2
KAW 203	Gotthardpass	686700/156700	2050	14.6±1.5	7.7
KAW 205	Gotthardpass	686450/158600	2200	13.8±0.8	7.5
KAW 207	Schwarzhorn	660680/132400	2530	14.2±0.6	7.2
KAW 223	Foppiano/Toce	674730/131750	900		3.2
KAW 224	Sand/Sertigtal	784060/177090	1890		14.4
KAW 233	Plattas/Zernez	802960/176900	1550		15.1
KAW 285	Zen Schmieden	635000/116650	1090		4.6
KAW 286	Cascata/Toce	675000/140180	1670	13.6±0.8	4.5
KAW 311	Cher/Gerental	675800/151275	2070	14.5±0.6	6.3
KAW 312	Wiss-Gufer/Gerental	674950/152450	1960		7.1
KAW 315	Massa	643672/131838	900	9.5±4.2	3.0
KAW 317	Ernen	656800/138275	1930	10.5±3.1	4.5
KAW 328	Lago di Cavloc	774080/139450	1900	27.0±3.9	14

(*) Standard deviation (1σ) for the fission track ages is about 10%.

TABLE 1a -

Sample N°	Locality	Coordinates	Elevation in meters above sea-level	Alpine Biotite Rb-Sr Ages in M.y.	Apatite Fission-Track Age (*) in M.y.
KAW 357	Serra/Zwischbergen	652670/113500	1280	12.2±2.8	3.2
KAW 360	Massa	643500/132400	900		3.4
KAW 367	Saas Fee/quarry Bifig	637050/104900	1880		6.3
KAW 369	Cime di Pozzuoli	651600/100500	rock-fall	24.6±1.0	5.0
KAW 370	Bränd/Zwischbergen	651550/111300	1540	22.2±6.6	6.2
KAW 372	Torno Bognanco	662200/108150	500	14.4±0.6	3.3
KAW 374	Rottal-Egge/Almageller Tal	643300/106100	2450	27.6±1.1	7.0
KAW 375	Schönenboden/Furggtal	643150/101300	2270	26.7±4.7	6.4
KAW 376	Weitsand/Furggtal	641900/102750	2140	26.1±1.5	5.6
KAW 377	Saas Fee	638300/106900	1800	26.1±2.7	5.5
KAW 384	Lago Scuro	687900/148150	2250		6.2
KAW 386	Lago Scuro	687900/148150	2250		6.0
KAW 394	Val Nalps	700300/161950	2250		8.8
KAW 395	Val Nalps	700300/161750	2300		9.4
KAW 397	Val Nalps	701590/166120	1860		8.1
KAW 399	Niedere Alp/Nanztal	639700/122800	1720		3.5
KAW 400	Nanztal	639550/124500	1480		3.4
KAW 401	Gebidem/Nanztal	638400/124500	2300		5.6
KAW 402	Saas Fee	637050/104900	1880		6.4
KAW 403	Breithorn/Mattertal	630700/110150	2900		10.4
KAW 404	Embd	630200/117900	1200		4.9
KAW 405	Passo Monte Moro	642100/ 94100	2870	28.8±1.1	9.6
KAW 408	Varzo - Trasquera	660750/118400	1080	12.7±2.2	2.8
KAW 409	Spitzhörnli/Nanztal	642100/123600	2600	12.0±1.9	6.7
KAW 411	Mezzalama	624800/ 84800	3020	32.1±1.2	11.3
KAW 417	Alagna/Val Sesia	638700/ 79800	1270		8.5
KAW 459	Tros - Stal/Unteralptal	693420/162000	1970		8.5
KAW 504	Carmine Inferiore	698100/ 99650	300		12.3
KAW 506	Candoglia/Toce	676800/ 91750	210		11.2
KAW 509	Forno/Val Strona	664350/ 87300	1100		9.2
KAW 550	Ponte Baffo/Val Masino	768800/117000	560	23.4±1.6	12.1
KAW 553	Codera/Bergell	757150/123050	800	21.3±2.1	13.5
KAW 572	Mergozzo/Toce	678900/ 90500	205		11.4
KAW 575	Tunnel Val Cristallina	708810/160470	1910		9.0
KAW 576	Tunnel Val Cristallina	708770/160440	1910		8.8
KAW 578	Tunnel Val Cristallina	705390/160110	1910	15.3±1.1	8.9
KAW 581	Tunnel Val Cristallina	707370/160220	1910	15.1±1.8	8.6
KAW 699	Val Sesia	639800/ 75300	1250		8.6
KAW 775	Fextal	779700/139000	2370		14.7
KAW 778	Bernina-road	796850/145350	2160		17.4
KAW 956	Ca Rotte/Malenco	784300/131300	1450		7.4

(*) Standard deviation (1σ) for the fission track ages is about 10%.

are indicated by a double circle on Map 1. The youngest ages (< 5 m.y.) are found in the Simplon area and in southwestern parts of the Gotthard and Aar massifs. From there, the ages increase gradually outward.

The distribution of the apatite fission-track ages does not conform to the general tectonic structures and the metamorphic isograds of the Alps. The fission-track isochrons cross the Gotthard and Aar massifs and the Pennine region producing an asymmetric picture (Map 1).

c) Interpretation

The apatite fission-track ages appear to be unrelated to any known geological event such as an igneous or a metamorphic phase. However, their systematic regional distribution suggests a relevant geological meaning. From laboratory experiments of the track stability and from the application of the fission-track method to various geological problems, it is now well established that apatite fission-track ages of plutonic and metamorphic rocks are cooling ages (WAGNER (1968)). In the case of the Central Alps, the apatite fission-track ages date the time when the rock temperature was 120 ± 20°C during the postmetamorphic cooling process (WAGNER and REIMER (1972)).

In annealing studies, a relatively low fission-track stability in apatite was observed at elevated temperatures (FLEISCHER *et al.* (1965), NAESER and FAUL (1969), WAGNER (1968), WAGNER (1972), MÄRK *et al.* (1973)). Most experiments, however, were conducted under « dry-air » conditions which limit their geological application. According to BURCHART and REIMER (1972), liquid fluids might also have some influence on the track stability. Therefore, additional annealing experiments more closely simulating natural conditions are needed for a better understanding of the apatite fission-track « clock ». The most important parameter which influences the track stability is temperature. Chemical variations in the composition of the apatites seem to have little influence. The thermal track-fading data of the various experiments agree very well, with the exception of the data by MÄRK *et al.* (1973); those authors worked partly with fission-tracks which had been already affected by natural annealing. From the annealing experiments (of up to one year in duration) the critical temperatures at which tracks fade are extrapolated to geologic time. Track accumulation does not follow a simple « off-on » mechanism related to a specific temperature. A cooling apatite would succesively pass through three different temperature zones related to track stability: a zone in which no tracks are recorded

TABLE 2 — Upper and lower temperature thresholds, for various cooling rates, between which fission-tracks in apatite are only partially stable.

Cooling rates (degrees per year)		1°/10⁷y	1°/10⁶y	1°/10⁵y	1°/10⁴y	1°/10³y	1°/10²y	1°/10y
Temperatures	upper threshold (*)	150	160	170	185	200	215	230
(in °C)	lower threshold (**)	40	45	55	70	85	105	125

(*) Above which no tracks are stable.

(**) Below which all tracks are stable.

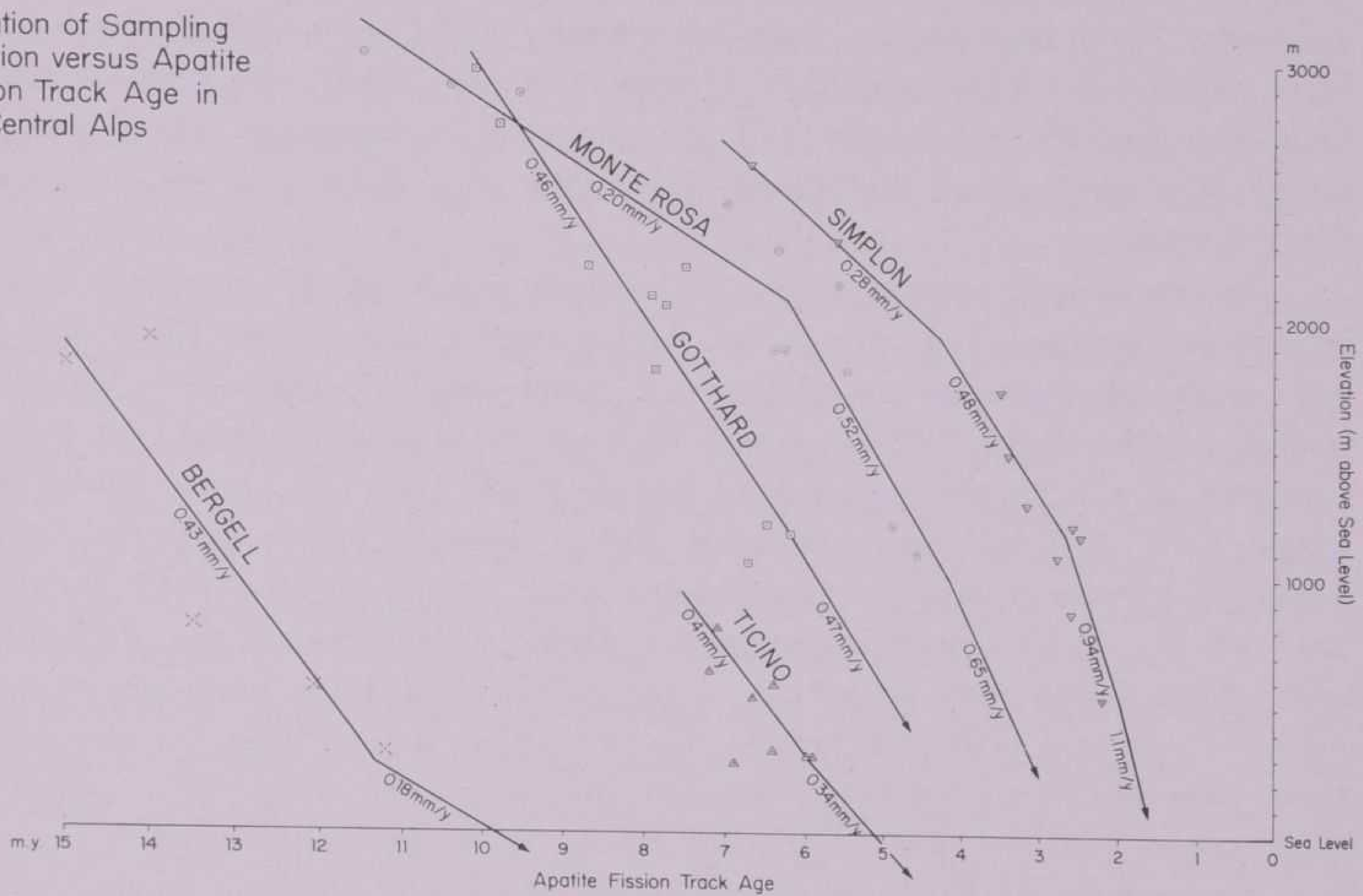
due to complete track fading; a zone in which tracks are partially recorded; and finally a zone in which tracks are completely recorded. The threshold temperatures between these zones depend on the cooling rate. They are higher with a faster cooling rate. The values for these temperatures are given in Table 2 and are extrapolated from experimental data. The general validity of the extrapolation was recently confirmed by NAESER and FORBES (1976). For cooling rates typical of the postmetamorphic history of the Central Alps, the upper and lower threshold temperatures can be assumed to be about 180°C and 60°C, respectively. As a consequence, instead of a singularly defined blocking temperature below which the fission-tracks are suddenly accumulated, there is a rather broad transitional zone of partial track recording. Hence, the fission-track age represents some time during the cooling process when the temperature was within the zone of partial track stability. An interpolation to a fixed temperature can be made and would be about the temperature at which half of the tracks become stable. In the case of the cooling rates typical for the Central Alps, this corresponds, for apatite, to a temperature of 120 ± 20°C. It should be noted that the temperature values given for the various degrees of track stability (Table 2) depend to some extent on the etching and counting conditions. Therefore, identical experimental conditions must be consistently applied not only during the dating but also for the annealing studies.

The observed regularities of the apatite fission-track ages are readily explained by developing a model in which the post-metamorphic cooling of the Alps is essentially controlled by uplift and erosion (CLARK and JÄGER (1969)). In the proposed uplift-cooling model, the higher part of a vertical rock column passes the isotherm critical for track stability before the lower part. Hence, if the age measurements are sufficiently precise, increasing ages would be expected with higher location. This explains the observed trend that, for topographically higher sampling locations in the same area, older apatite fission-track ages are found than for lower locations. From the slopes of the age vs. altitude curves (Fig. 1), paleo-uplift rates can be calculated provided no vertical tectonic displacement exists between the sampling locations.

The areal variations in fission-track ages reveal the regional uplift pattern. Any one age, therefore, directly gives the time which elapsed between passing the 120°C isotherm and reaching the surface. Thus, an average cooling rate (and an average uplift rate, if the geothermal gradient is known) can be calculated individually for each sample. In order to calculate the cooling rates below 120°C, the question arises which temperature should be used for « today ». One obvious possibility is to use the mean annual surface temperature T_a (Eidg. Landestopogr. (1965)). However, the cooling rates between 120°C and the mean annual surface temperature are only of limited geological interest. They are not simply related to the uplift rate and the geothermal gradient of the area because they are strongly influenced by the present geomorphology. Consequently, they cannot bé used for tectonic interpretations. A second possibility can be considered in which the present morphology of the Alps is replaced by a plain surface at an altitude of 2200 meters and a mean annual surface temperature of 1.5°C. The rock temperatures T_p of the sampling locations are calculated according to their depth below this surface by using the mean geothermal gradient of the area (30°C/km). The altitude of 2200 meters is chosen because the resulting temperatures for the various depths agree reasonably well with those actually measured in tunnels. Certainly, this model is very crude for the Alps. However, considering the youth of the Alpine morphology in comparison to the fission-track ages, the model is not too unrealistic.

Fig. 1

Elevation of Sampling Location versus Apatite Fission Track Age in the Central Alps



There is another theoretical possibility to explain the regionally changing ages, namely, bulged isotherms. Although this explanation cannot be completely ruled out, it is believed to be inconsequential because the observed large age changes over small distances (e.g., by an age factor of seven over only 30 km horizontal distance) would require geologically unrealistic heat domes.

The geological events dated by the apatite fission-track ages are of postmetamorphic age. This is compatible with the interpretation of the apatite fission-track ages as 120°C cooling ages during the postmetamorphic uplift. The apatite fission-track ages are also always younger than the corresponding mica Rb-Sr and K-Ar ages, which are for their part controlled by blocking temperatures of 500° to 300°C.

2) Rb-Sr, K-Ar, and U-Pb AGE DETERMINATIONS

a) Methods and results

Many of the Rb-Sr and K-Ar ages have already been published (GRAUERT *et al.* (1969), JÄGER and HUNZIKER (1969), ARNOLD (1972), HUNZIKER (1974). FREY *et al.* (1976), and PURDY and JÄGER (in press)). KÖPPEL and GRÜNENFELDER (1975) have analyzed several monazites from the eastern Lepontine area, the Bergell and the western Alps using the U-Pb technique. From the Bergell area Rb-Sr and U-Pb data have also been published by GULSON (1973), GULSON and KROGH (1973), and HÄNNY *et al.* (1975). The Rb-Sr and K-Ar techniques have been described by WÜTHRICH (1965), PURDY (1972), and PURDY and JÄGER (in press).

For mica dating, special care was taken in rock sampling and mineral separation. The samples were usually collected as single blocks from homogeneous rocks, the sample size being at least 30 kg. Quite frequently, two white mica generations are present in the same rock, and the homogeneity of the white mica concentrates had to be checked by X-ray techniques (CIPRIANI *et al.* (1968)). To separate the two white mica generations, muscovite and phengite, the concentrates were repeatedly ground in alcohol, dryed, and sieved. Very thin mica flakes can be obtained by this technique.

The comparison between apatite fission-track and biotite Rb-Sr ages is meaningful only for biotites which give young, Alpine cooling ages. Biotite Rb-Sr ages from lower grades of Alpine metamorphism with problematic interpretation had to be omitted. All the biotite Rb-Sr ages have been calculated as biotite-total rock isochrons (corrected ages) with the exception of sample KAW 370. The biotite Rb-Sr age of sample KAW 370 has been calculated with a normal $^{87}Sr/^{86}Sr$ ratio for the non-radiogenic strontium component (uncorrected age). The biotite-total rock isochron is based on the assumption that during the Alpine metamorphism the different minerals did exchange their strontium — the radiogenic and the non-radiogenic component — within a total rock sample. JÄGER (1970) showed that, in the zone of Alpine staurolite, strontium homogenization did occur. In rocks with rather low Rb/Sr ratios, corrected and uncorrected biotite Rb-Sr ages agree within the error limit. Concordance of K-Ar and Rb-Sr biotite ages can be used to decide which of the biotite Rb-Sr ages has geological meaning (PURDY and JÄGER (in press)).

Muscovites have lower Rb/Sr ratios than biotites, phengites being intermediate. Low Rb/Sr ratios make the young Rb-Sr age determinations difficult; quite often, high error limits make a precise determination and comparison with other data impossible. Alpine white mica Rb-Sr ages can be measured with high precision only from rocks with exceptionally high Rb/Sr ratios, very acidic granites, gneisses, and pegmatites.

For the age calculation, the following decay constants have been used:

$$\text{Rb-Sr} \;-\; \lambda = 1.47 \times 10^{-11} y^{-1}$$
$$^{85}Rb/^{87}Rb = 2.591$$
$$\text{K-Ar} \;-\; \lambda_{\varepsilon} = 0.585 \times 10^{-10} y^{-1}$$
$$\lambda_{\beta} = 4.72 \times 10^{-10} y^{-1}$$
$$1.19 \times 10^{-4} \text{ moles } ^{40}K/\text{mole K}$$

b) Interpretation

For a detailed discussion on the interpretation of Rb-Sr and K-Ar mineral ages, see PURDY and JÄGER (in press). In the amphibolite facies - staurolite zone of Alpine metamorphism, it is evident that biotite Rb-Sr and K-Ar ages date a late, post-metamorphic cooling state. In the Simplon region, biotites from open fissures, which must be younger than the compressive phase of metamorphism, give the same K-Ar and Rb-Sr ages as the biotites from the foliated gneisses in the same vicinity (Jäger *et al.* (1967), and Purdy and Stalder (1973)). In the Val Verzasca - Ticino area, post-metamorphic pegmatites which cut the well oriented gneisses give the same mica Rb-Sr and K-Ar ages as the gneissic country rocks.

By comparing the transition from pre-Alpine to Alpine mica Rb-Sr ages to metamorphic isograds, blocking temperatures for the Rb-Sr systems in micas have been derived. The zone of intermediate (Alpine - pre-Alpine) biotite Rb-Sr ages is situated in the zone of Alpine stilpnomelane, indicating a temperature of 300 ± 50°C for the opening and the blocking of the Rb-Sr system in biotite. The boundary between Alpine and pre-Alpine white mica Rb-Sr ages is situated somewhat outside the staurolite - chloritoid transition. Thus, an opening and blocking temperature of 500 ± 50°C had been postulated. Because white micas (muscovites and phengites) can form below this temperature, their Rb-Sr system in this case will be closed immediately after their crystallization. In the lower grade of metamorphism, therefore, white mica Rb-Sr ages date the time of mica formation. Using this approach, the climax of the Lepontine phase of Alpine metamorphism, the only phase considered in this paper, had been dated by Hunziker (1970, 1974), and Jäger (1973). In the zones of low grade metamorphism surrounding the high grade Lepontine area, these authors find Rb-Sr white mica ages of 35 - 40 m.y. which are interpreted as formation ages.

Armstrong *et al.* (1966) demonstrated that biotites give identical Rb-Sr and K-Ar ages in the area of the Lepontine phase of Alpine metamorphism. Not only are the cooling ages the same, but in several cases identical intermediate Alpine - pre-Alpine ages have been found. Therefore, the blocking temperature for the biotite K-Ar ages must be the same as the Rb-Sr blocking temperature which is 300 ± 50°C. By comparing the white mica K-Ar ages to the Rb-Sr data, Purdy and Jäger (in press) determine a blocking temperature of 350°C for the K-Ar system in muscovite and phengite. This blocking temperature has a higher uncertainty than the Rb-Sr blocking temperatures.

Köppel and Grünenfelder (1975) interpret the U-Pb ages on monazites as crystallization ages. Hunziker and Jäger (in preparation) interpret these ages as cooling ages. Two facts supporting this second interpretation will be mentioned here; other arguments will be presented in section IV, *4*. In the Leventina - Ticino area, the monazite ages increase with tectonic height within the pile of nappes, samples from higher nappe units giving older monazite U-Pb ages than samples from deeper units. In this area, the same effect has been observed with the much younger muscovite K-Ar ages which cannot be interpreted as formation ages; the age difference is about the same as the monazite U-Pb age difference. This demonstrates that the monazite U-Pb ages cannot date the climax of the Lepontine phase of metamorphism. Why should the temperature maximum be reached in the higher situated rocks before the lower ones? But it is obvious that the higher rocks cool earlier than the deeper ones. Furthermore, in the Monte Rose region, U-Pb monazite ages date the time of a later metamorphism. The maximum temperature reached during this metamorphic phase has been determined by $^{18}O/^{16}O$ measurements to 530°C (FREY *et al.* (1976)). The Rb-Sr total rock system is older than this phase, the U-Pb age did not survive. Therefore, in this paper we follow the interpretation of HUNZIKER and JÄGER (in preparation), which assumes a blocking temperatue of 530°C for U-Pb in monazites.

III. COMPARISON OF DIFFERENT AGES

In principle, the different cooling ages measured on coexisting minerals should allow the study of the cooling history of a rock from 530°C to the present temperature. However, in practice, there are often limitations presented by the rock mineralogy, low maximum temperatures, etc. The biotite Rb-Sr and apatite fission-track ages are well suited for comparison because both were determined on more than forty rocks from the Central Alps (Table 1). The difference between the ages of these two minerals gives the time span during the cooling from 300°C to 120°C and indirectly is a measure for the uplift rate within this temperature interval. The differences between the biotite Rb-Sr and the apatite fission-track ages range from 5 m.y. to 21 m.y. They are shown for the various localities on Map 2. Their distinct regional distribution proves that this age difference has a geological significance. The smallest age differences (5 to 7 m.y.) are found for the Gotthard and the Bergell massifs; the Walliser Alps southwest of the Simplon-Centovalli fault give the largest age differences (15 to 21 m.y.).

Comparison of Map 2 with Map 1 shows that the areas with the fastest cooling and uplift are not identical for the two temperature intervals 300° - 120°C and 120°C-present surface temperature. This indicates temporal and regional changes of cooling and uplift in the Central Alps. Cooling curves for samples from the same region are similar, but they differ significantly from one region to another (Figures 2a - 2f). The regions with similar cooling and uplift history are mapped in Figure 3. The Ticino (Fig. 2b), the Gotthard (Fig. 2c), the Simplon - Antigorio (Fig. 2d), and the Monte Rosa (Fig. 2f) regions are well defined by their uplift patterns. The uplift pattern of the Bergell massif (Fig. 2a), and the Oberwallis (Fig. 2e) regions are less uniform and may be further divided with an increased sampling density.

For the following geological discussion, one to three representative samples were selected from each region; their locations are shown in Fig. 3. They are selected on the basis of their different cooling ages, age accuracy, clear age interpretation and characteristic behavior.

All available age data have been compiled in Table 3 for these samples representative of the various regions. The mean ages of the biotite Rb-Sr and biotite K-Ar ages have been used. All ages are cooling ages with the exception of the phengite Rb-Sr age from the Monte Rosa region (34.5 m.y., FREY *et al.* (1976)). Assuming the blocking temperatures as discussed in section II, cooling rates have been calculated for the corresponding temperature intervals. These cooling rates are the average values for the threshold intervals and do not reflect variations within the intervals. The cooling rate for the 350 - 300°C interval has a high uncertainty because the age difference between these two cooling stages is rather small and, in the case of the Bergell

Fig. 2a - 2f

Cooling History of Different Samples from a Particular Region Derived by Biotite Rb-Sr and Apatite Fission Track Ages

KAW. sample numbers are given in the Figures
present rock temperature according to plain surface model

Fig. 2a
BERGELL

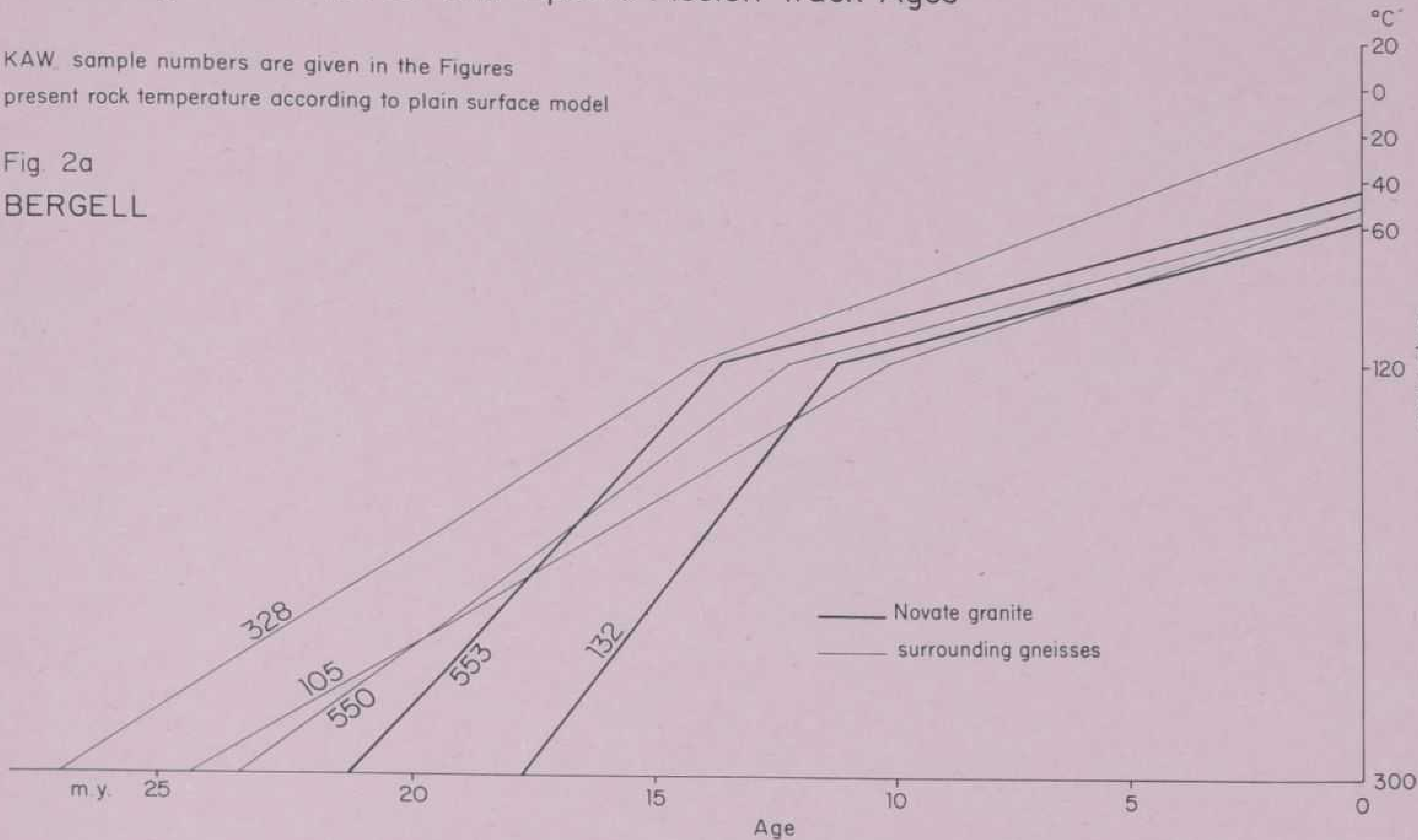


Fig. 2b
TICINO

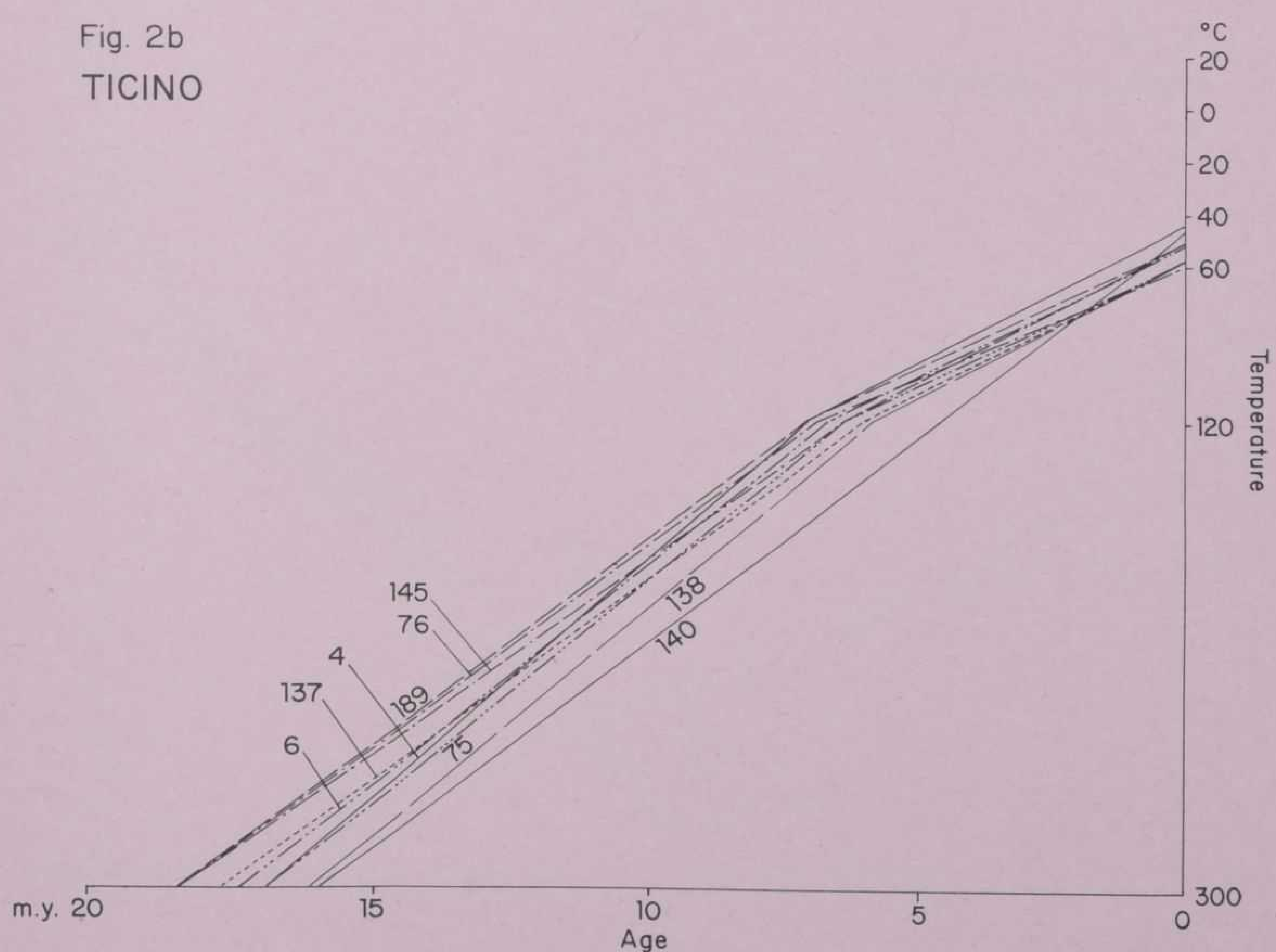


Fig. 2c
GOTTHARD

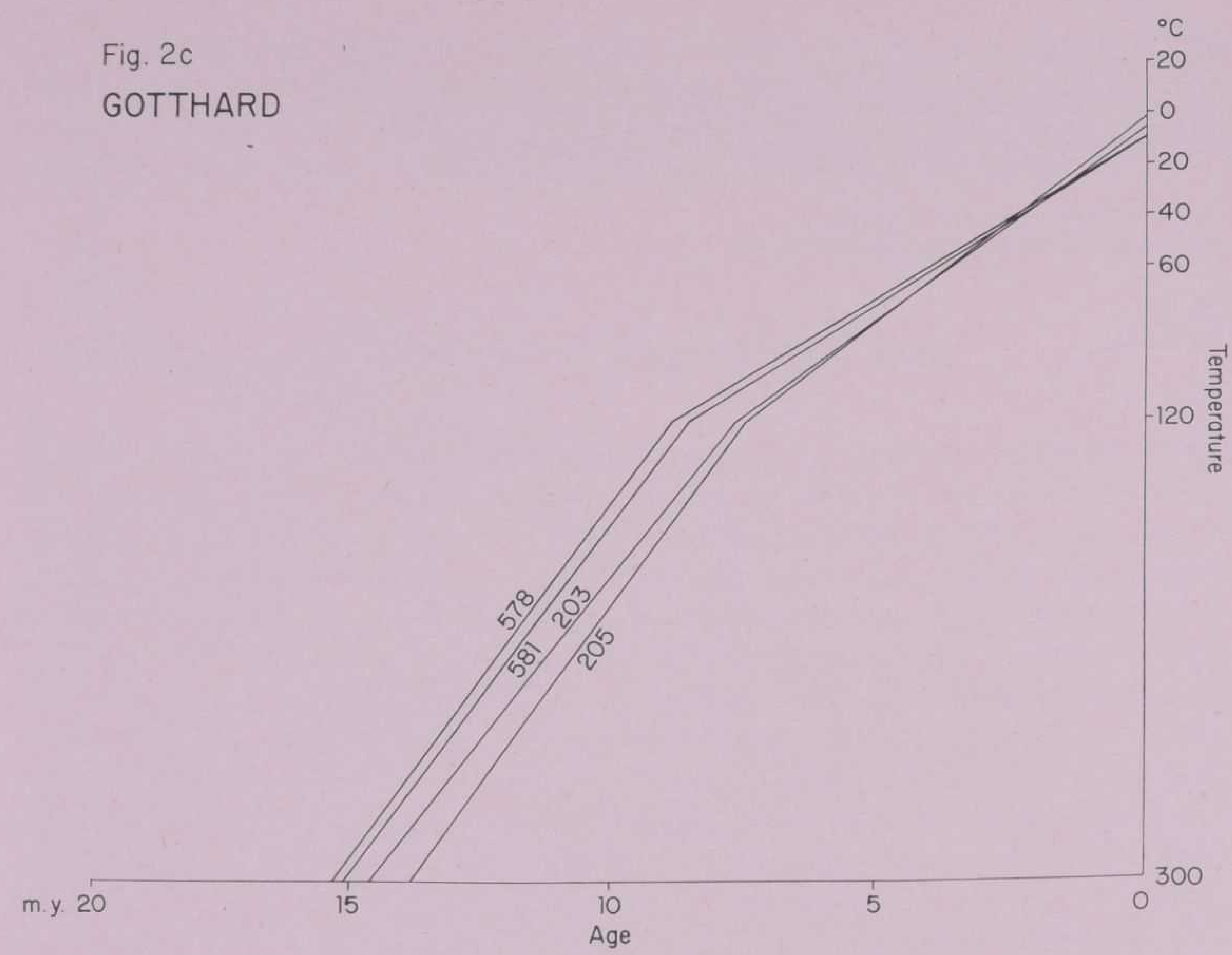


Fig. 2d
SIMPLON - ANTIGORIO

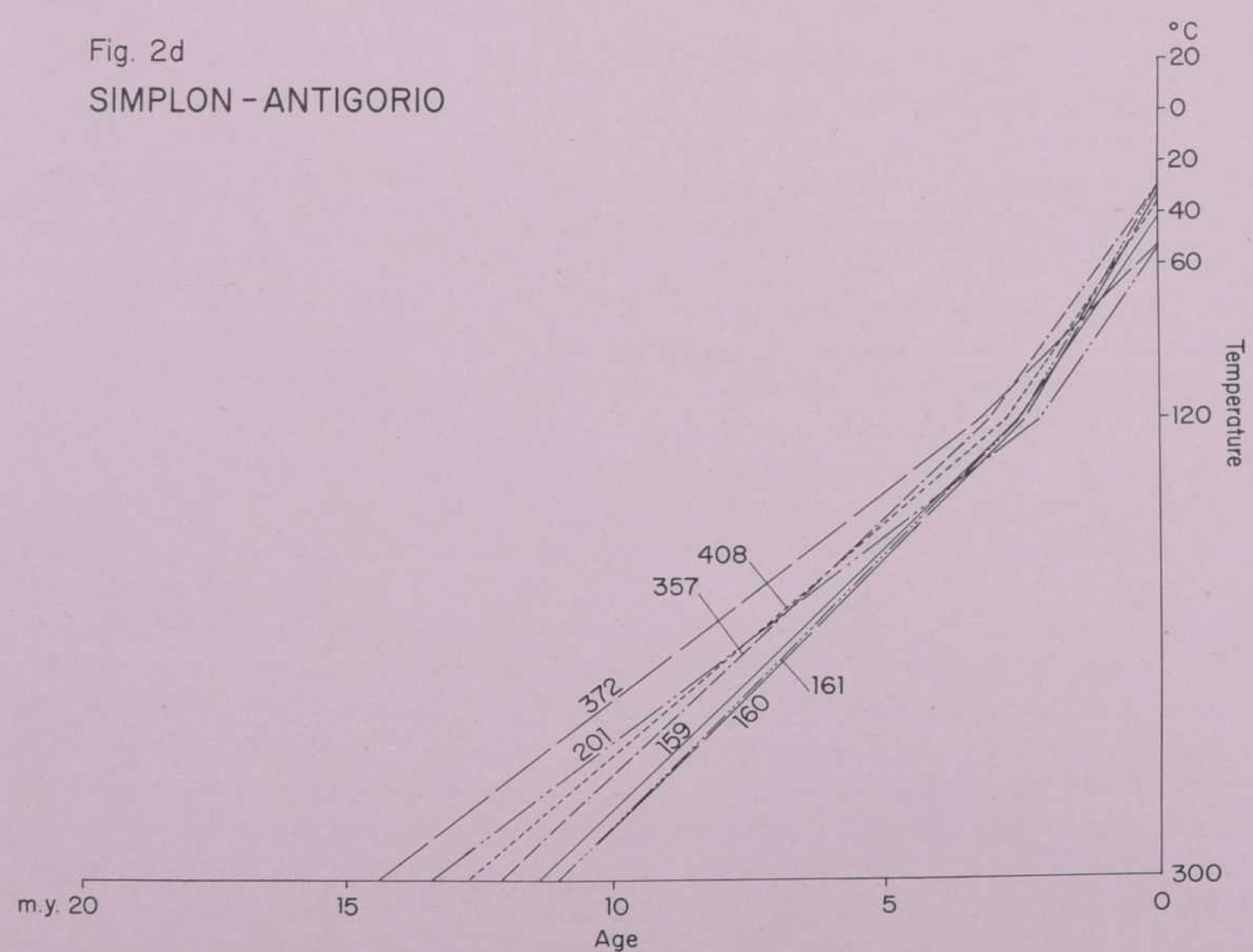


Fig. 2e
OBERWALLIS

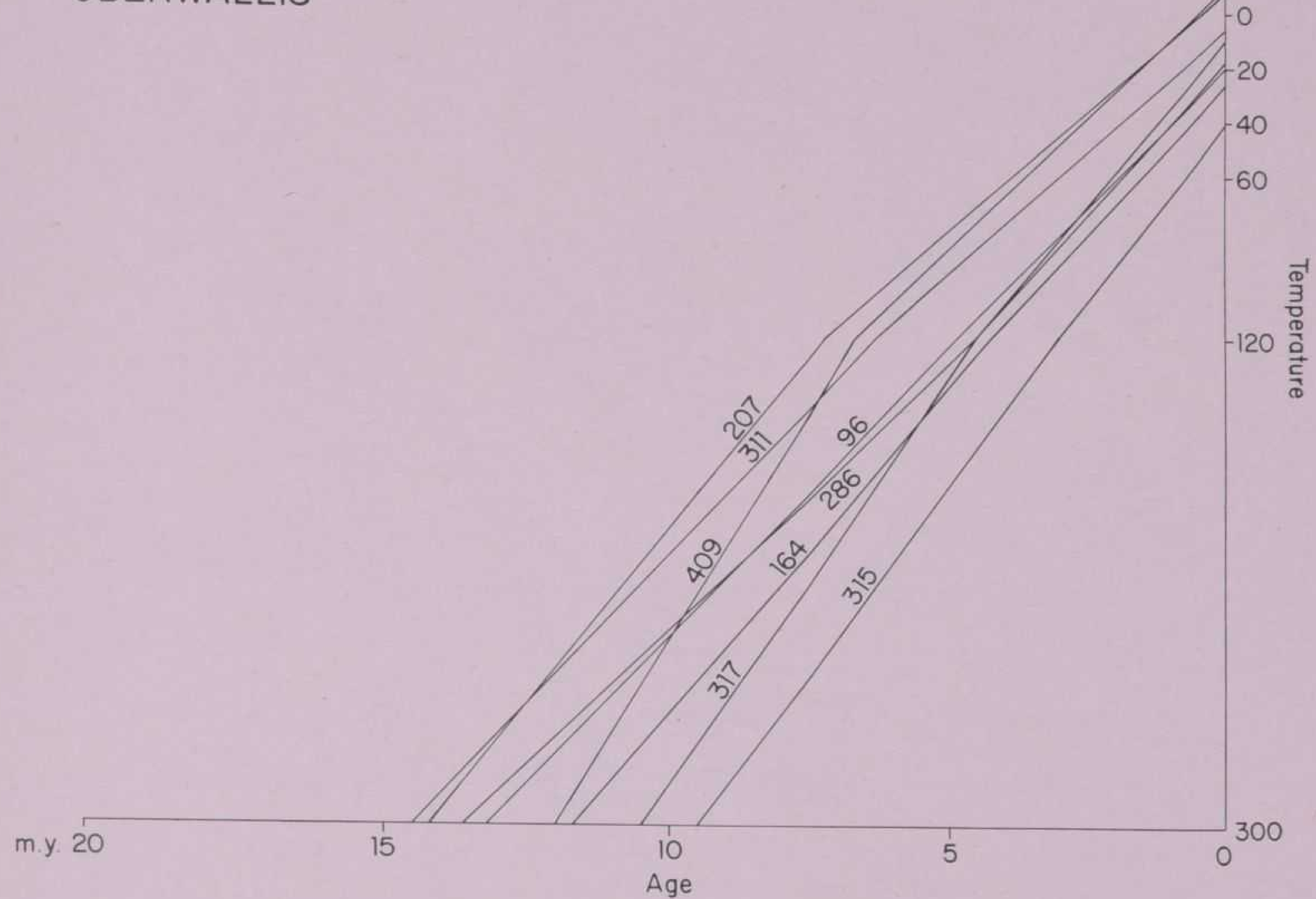
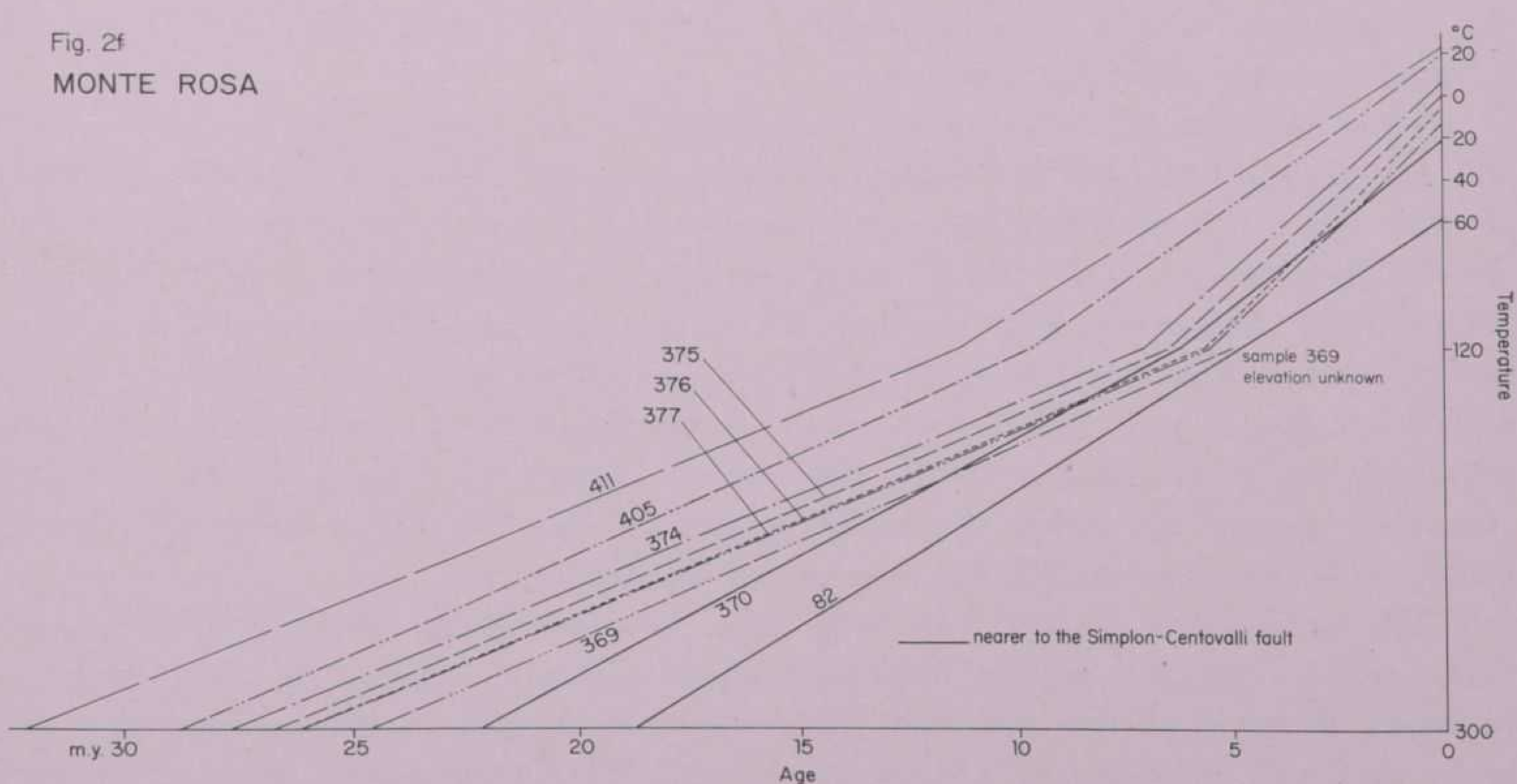
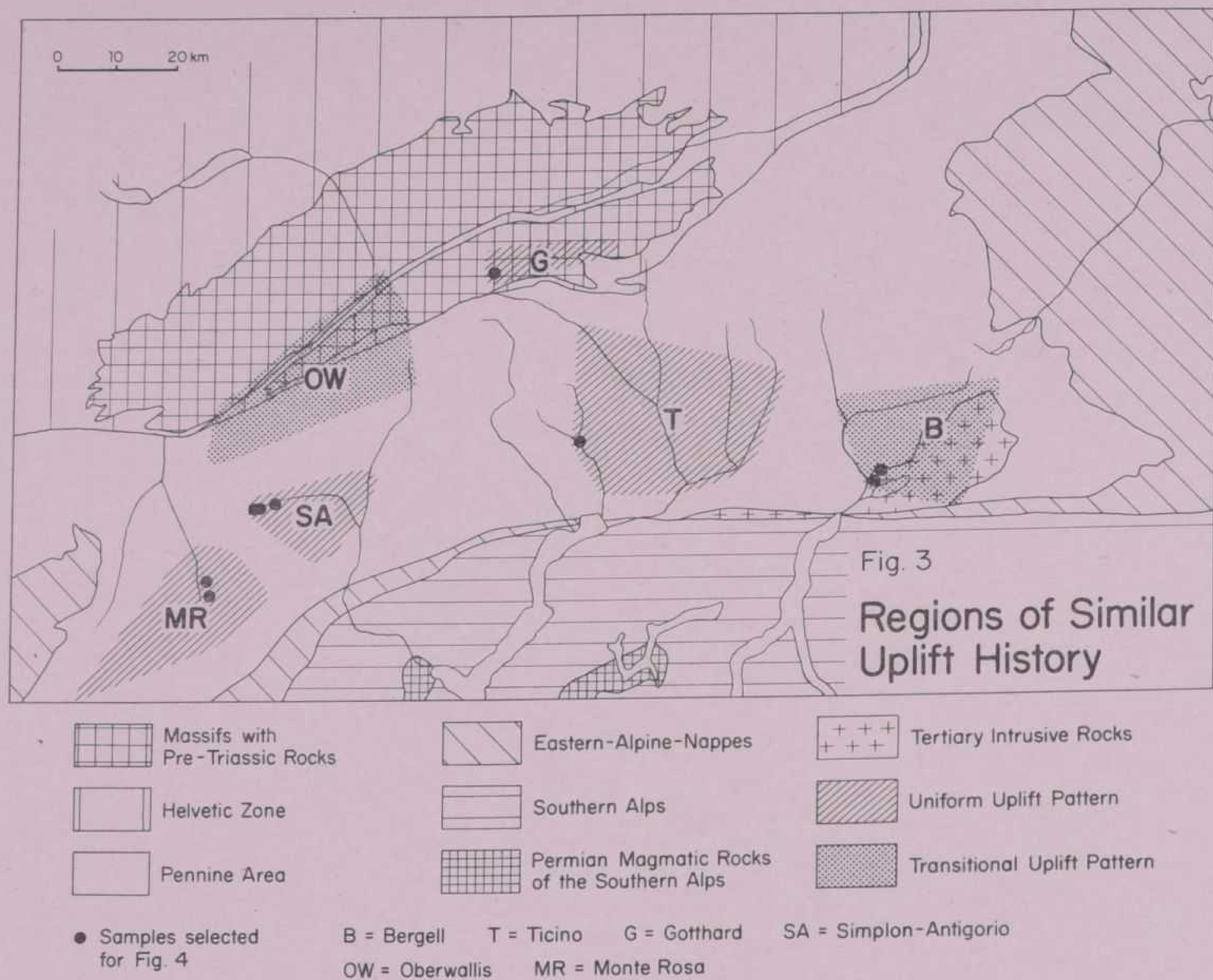


Fig. 2f
MONTE ROSA





massif, it is even smaller than the error limits on the two age values. The cooling rates between 120°C and present rock temperatures have been calculated according to the two models explained in Section II, *1, c*. The cooling rate of 20°C/m.y. from 460° to 300°C in the Monte Rosa region can be considered as a minimum value because the temperature reached a maximum there of 460°C, 34.5 m.y. ago. This temperature could have prevailed for some time.

From the data in Table 3, the main trends of the cooling history of the Central Alps emerge (Fig. 4): The cooling in the Bergell and Ticino regions has generally slowed; the Gotthard region seems to have cooled rather constantly at 18°C/m.y. The Simplon-Antigorio and Monte Rosa regions have experienced a more complex history, their cooling was quite rapid in the early stages, and after a period of slower cooling, the cooling rate has again increased considerably. However, cooling to the same temperatures took place much earlier in the Monte Rosa region than in the Simplon-Antigorio region. Below 300°C, the cooling pattern of Fig. 4 looks strikingly symmetric around the stable Gotthard region; towards the east, cooling has slowed and towards the west, cooling has accelerated during the past.

The cooling rates not only vary with time, they also change within small distances. Such variations of the cooling rates over short distances cannot be explained by variations of the geothermal gradient. These regional changes in the cooling rates are better explained by assuming a differential uplift. This is supported by the fact that the area with the youngest cooling ages is also the area of actual maximum uplift.

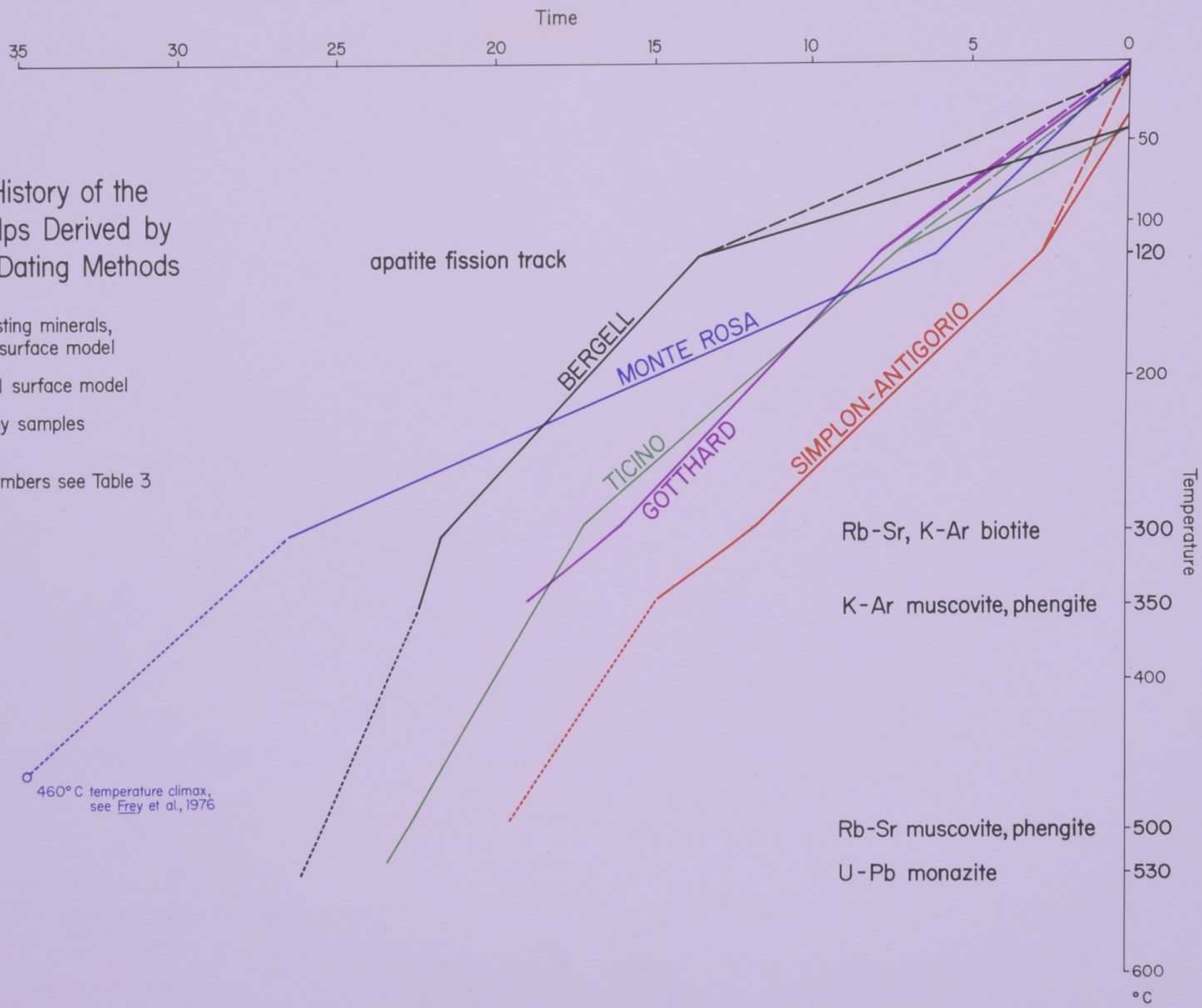


Fig. 4

Cooling History of the Central Alps Derived by Different Dating Methods

_____ coexisting minerals, plain surface model

_ _ _ actual surface model

.... nearby samples

For sample numbers see Table 3

TABLE 3 — Cooling and Uplift Rates of the Central Alps.

region	locality rock, sample No.	elevation above sea level, meters	present rock temperature T_a actual surface, °C	present rock temperature T_p plain surface, °C	cooling rate 120°C-T_a, °C/m. y.	cooling rate 120°C-T_p, °C/m. y.	(120°C) apatite fission-track age, m. y.	300-120°C cooling rate, °C/m. y.	(300 °C) Rb-Sr, K-Ar biotite age, m.y.	350-300°C cooling rate, °C/m.y.	(350°C) K-Ar muscovite phengite age, m.y.	earlier cooling rates; °C/m.y.	(500°C) Rb-Sr muscovite, phengite age, m.y.	(530°C) U-Pb monazite age; m.y.	uplift rates, mm/y: 120°C-T_a (5)	uplift rates, mm/y: 120°C-T_p (5)	uplift rates, mm/y: 300-120°C (5)	uplift rates, mm/y: at 120°C (6)
Bergell	Novate-Codera-granite KAW 553	800	9	44	8	6	13.5	22	21.6	71	22.3	530-350°C 49	—	26.0(2) nearby sample	0.3	0.2	0.7	0.43
Ticino	Brione Verzasca-gneiss KAW 4	800	9	44	16	11	7.1	19	16.8	38	18.1	530-350°C 38	—	22.8(2)	0.5	0.4	0.6	0.4
Gotthard	Fibbia-gneiss KAW 203	2'050	2	6	15	15	7.7	23	15.7	17	18.7	—	—	—	0.5	0.5	0.75	0.46
Monte Rosa	Monte Rosa-gneisses KAW 375, 376	2'200	2	2	20	20	6.0	9	26.4	—	excess argon, ages too high	460(1)-300°C 20	34.5(3) nearby sample	—	0.7	0.7	0.3	0.4
Simplon-Antigorio	Simplon-gneisses KAW 159, 160, 161	1'070	7	35	43	33	2.6	20	11.4	16	14.5	500-350°C 33	19.0(4) nearby sample	—	1.4	1.1	0.7	0.94

(1) 460°C maximum temperature of the Alpine metamorphism in this area, see FREY et al., 1976.

(2) KÖPPEL and GRÜNENFELDER, 1975.

(3) Sample KAW 377, FREY *et al.*, 1976

(4) Sample KAW 358, JÄGER and HUNZIKER, 1969.

(5) Assuming a geothermal gradient of 30°C/km.

(6) Derived by the elevation dependence of apatite fission-track ages.

If uplift and erosion govern the cooling history, the high temperature conditions during the metamorphism must have been caused, to a great extent, by deep tectonic burial. This supports the theory of E. NIGGLI (1961) and E. NIGGLI and C. R. NIGGLI (1965), who consider the tectonic burial to be responsible for the increase in pressure and temperature during the Alpine orogeny. In addition, CLARK and JÄGER (1969) were able to show that during the Lepontine metamorphism, the geothermal gradients must have had normal values around 30°C/km. Recently, M. FREY (personal communication) reached similar conclusions based on mineral equilibrium studies. This means a relatively constant geothermal gradient from the time of the metamorphism through the cooling period. Therefore, cooling rates can be transferred into uplift rates without introducing a large error. Using a geothermal gradient of 30°C/km, uplift rates have been calculated for the 300°-120°C and the 120°C - present rock temperature intervals (Table 3). These uplift rates are average values for each temperature interval, as are the cooling rates.

These uplift rates can be cross-checked with those determined independently from the altitude effect of apatite fission-track ages. The slopes of the curves in Fig. 1 are the uplift rates at the time indicated by the fission track age. The uplift rates derived by this method for a sample should be between those for the 300°-120°C and the 120°C - present rock temperature intervals. The weakness of this aproach lies in the possibility that tectonic displacements may have occurred between the sampling locations; nevertheless, the uplift rates derived from the two different approaches (Table 3) for the representative samples are in agreement.

The uplift rates from Fig. 1 also reveal temporal changes of uplift for the various regions of the Central Alps: The slowing of the uplift in the Bergell about 11 m.y. ago; the acceleration of uplift in the Monte Rosa and Simplon-Antigorio regions about 6 and 3 m.y. ago, respectively; the rather constant uplift rate of the Gotthard region. The Ticino region would require more sampling from different elevations. These temporal changes agree very well with those derived from the combination of biotite Rb-Sr and apatite fission-track ages.

Finally, we would like to point out that the pattern of the different cooling ages and their distinct regional distribution gives us confidence about the values used as blocking temperatures which have been derived independently and by different methods.

IV. DISCUSSION OF THE INDIVIDUAL REGIONS

1) Ticino: In this region, especially the root-zone near the Bergell granite, the Lepontine metamorphism was most intense, with a temperature maximum above 600°C. In this zone of high-grade metamorphism, it is impossible to date the mineral formation. Following the interpretation of HUNZIKER and JÄGER (in preparation), even U-Pb ages of monazites date a cooling stage. We can only conclude from the formation ages of 35 to 40 m.y. around the high-grade region that the main metamorphism happened at the same time. There is no geological argument for a later metamorphism in the high-grade zone, but there is good geological evidence for the Lepontine metamorphism being older than 30 m.y. The Bergell granite is post-metamorphic, younger than the Lepontine metamorphism. Zircons from the three main types of granitic rocks from the Bergell intrusion give U-Pb ages of 30.3 m.y. (GULSON and KROGH (1973)). Thus, the Lepontine metamorphism must be older than 30 m.y. According to KÖPPEL and GRÜNENFELDER (1975) and HÄNNY *et al.* (1975), the climax of the Lepontine phase should be younger. KÖPPEL and GRÜNENFELDER (1975) argue that the monazite U-Pb ages date the crystallization and not a cooling stage, as previously discussed in section I, *2*, *b*., but this assumption cannot be supported. In addition to the mentioned age increase with tectonic height, the monazite U-Pb ages increase gradually from north to south, towards the root region. This regional trend is also observed for the younger mica ages. By explaining the monazite ages as formation ages, one is forced to assume a movement of the hotest region from south to north - a movement which is parallel to the differential uplift. HÄNNY *et al.* (1975) determined Rb-Sr and U-Pb ages in the Ticino area, west of the Bergell granite. They report an age pattern similar to our Ticino data: Rb-Sr biotite ages of 18.4 - 19.4 m.y.; a Rb-Sr muscovite age of 20.5 $\pm$ 0.6 m.y.; and U-Pb monazite ages between 23 and 24 m.y. On three small adjacent whole rock samples, these authors report an isochron age of 22 $\pm$ 6 m.y. Concordance of these data is used as an argument that the climax of a second metamorphic phase has been dated. The mineral data of HÄNNY *et al.* (1975) can fit our proposed cooling pattern for the Ticino area. The total-rock isochron, using centimeter size samples, can be considered as a mineral isochron. By using smaller and smaller sample sizes, there would be a transition from a total-rock to a mineral isochron.

The question now arises, when did the metamorphic temperature reach its maximum? Our mineral formation ages of 35 to 40 m.y. date the time of mica formation. During this time interval, there would still be progressive metamorphism with the production of some fluids for mica crystallization. Fluids might be produced not only by rising temperature but also by local movements. Other local parameters such as schistosity of a rock and local chemistry might also influence the formation of new minerals. Thus, we do not think that it will ever be possible to give a smaller range for the time of mica formation. If we accept 35 to 40 m.y. to be the progressive side of the temperature maximum, we have a short time span for the high temperature interval. In the root-zone of the Lepontine region, KÖPPEL and GRÜNENFELDER (1975) report monazite U-Pb ages between 27 and 28 m.y. Thus, the time interval for the change from increasing to decreasing temperature is only in the range of 7 to 13 m.y. This is regarded as too short for two thermic phases.

The Ticino area represents the center of the Lepontine metamorphism; the deepest tectonic units of the whole Alpine chain are found there. If we assume that, in the high-grade root-zone, cooling to 600°C happened about 30 m.y. ago, we find an overall mean cooling rate of 20°C/m.y., a rather slow cooling. As shown in Table 3 , the cooling rates are faster in the high temperature region, the cooling slows to the average value in the range of 300° to 120°C, and is followed by still slower cooling to the present surface rock temperatures.

The uplift rate of the Ticino area, determined from the cooling rates and the age data, has consistently decreased from 1.3 mm/y about 20 m.y. ago to 0.4 mm/y (average over the last 7 m.y.).

2) Gotthard: This region is less well studied than the Ticino area. The eastern part, the Gotthard-Lukmanier area, shows a rather uniform uplift of 0.6 mm/y over the last 19 m.y. However, the uplift may have slowed slightly from 0.7 mm/y to 0.5 mm/y about 8 m.y. ago. Apatite fission-track ages in the Aaar massif north of the Gotthard pass reveal somewhat smaller uplift rates of 0.4 mm/y during the last 8 m.y. (SCHAER *et al.* (1975)). The uplift history of the Gotthard region (below 350°C) resembles that of the Ticino region; there are insufficient data in the high temperature range for the Gotthard region. In support of the lower grade of Alpine metamorphism in the Gotthard area, phengite Rb-Sr formation ages of 36 m.y. have been found in the vicinity of the white mica cooling ages (JÄGER, 1970). The uplift history of the western end of the Gotthard massif is different from the Gotthard-Lukmanier area and is more closely associated with the transitional Oberwallis region (Fig. 3).

3) Monte Rosa and Simplon-Antigorio regions: Both these regions are separated by the Simplon-Centovalli fault which offsets all the Alpine mineral age zones. The Monte Rosa region cooled before the Simplon-Antigorio region. The comparison of the biotite Rb-Sr and apatite fission-track ages gives some information on the age of the Simplon-Centovalli fault. On Map 2, showing the regional distribution of the difference between the biotite Rb-Sr and apatite fission-track ages, the Simplon-Centovalli fault sharply divides age differences of $>$ 15 m.y. in the southwest and age differences $<$10 m.y. in the northeast. On Map 1, using only the apatite fission-track ages, the distinction between the two sides of the fault is still evident. This indicates that tectonic activity along this fault started quite early (more than 10 m.y. ago) and that the fault was still active in the last 3 m.y.

Below 300°C, the uplift rates in both regions increase with time from 0.3 to 0.7 mm/y about 6 m.y. ago in the Monte Rosa region, and from 0.7 to 1.1 mm/y in the Simplon-Antigorio region about 3 m.y. ago. This is in agreement with the actual present day uplift rates, measured by the Eidgenössische Landestopographie (in preparation). Uplift measurements along the Rhone valley show a distinct maximum near Brig, just north of the Simplon area where the youngest apatite fission-track ages are found.

The high heat flow difference of 0.92 heat flow units between the Simplon and the Gotthard tunnel has been explained by CLARK and JÄGER (1969) as due mainly to differential uplift. These authors assumed a constant cooling rate from 300°C to the present temperatures. The new fission-track data give even stronger support to the differential uplift theory; the fission-track ages are much younger in the Simplon (2.6 m.y.) than in the Gotthard region (7.7 m.y.).

4) Bergell region: The Bergell intrusion is a rather complex intrusive sequence in the eastern part of the Pennine root zone. We have selected the Novate granite from the western part of the Bergell complex as a representative granite. From geological evidence, the Novate granite seems to be the youngest granite of the whole intrusive series. This granite has been selected because many age data exist on different rock samples from this intrusion. Although the Bergell series is situated in the area of the highest grade of Alpine metamorphism, it cooled earlier to the 350°, 300° and 120°C temperatures than regions with lower grades of Alpine metamorphism. This means that the uplift through the 350°C temperature gradient has started soon after the climax of the metamorphism in accordance with the information reported by GULSON and KROGH (1973), who found zircon ages of 30.3 m.y. from three different types of granitic rocks, including the Novate granite. This age has also been measured on zircons from Bergell granite boulders embedded in molasse sediments in the Po plain and is interpreted as the crystallization age for all three granite types. Biotites from the same boulders give K-Ar ages of 27.7±1.3, 28.5±1.4, 27.8±1.3, and 28.3±2.6 m.y. We interpret these K-Ar ages as cooling ages to a temperature somewhat higher than 300°C because the faster cooling rate establishes a higher blocking temperature. This means that from 30.3 to 28 m.y., the temperature must have dropped from more than 670°C to a temperature slightly above 300°C, a cooling rate of about 150°C/m.y. This cooling rate is much faster than any other cooling rate found so far in the Lepontine metamorphic terrane. This rapid cooling means cooling from a magmatic state, not controlled by uplift and erosion, and that the Bergell granite, at least its upper part which produced the boulders, has intruded the cooling post-metamorphic country rock. Well developed zones of contact metamorphism in the northeastern part of the granite support this conclusion.

Recently we measured more ages of 38 m.y. to the east of the Bergell intrusion, the same age as in the other regions of the Lepontine metamorphism. This indicates again that the granite intruded into a cooling country rock. A question now arises concerning the formation of the Bergell granite in the time and the region of a rapid, early uplift. We think that the Bergell magma formation has been caused by the fast uplift, when the metamorphic temperature was still high. There are indications for additional magmatic activity in the area. To the west along the steeply dipping root zone, many pegmatites have been found. Towards the root-zone, from north to south, we find an increasing grade of metamorphism and higher cooling ages as compared to the Ticino area north of the root-zone. Again, we observe a causal connection between the magmatic activity and the high grade metamorphism with the early uplift. Thus, we feel that the Bergell granite is not a product of the Lepontine metamorphism, it is rather a product of the early and rapid uplift following the metamorphism.

The mica cooling ages in the Bergell area show a strong regional variation. Biotite Rb-Sr ages decrease from 29 m.y. just north of the Bergell granite to 18 m.y. in the Novate granite, which is situated 25 km to the southwest. Here the east-west age trend is superimposed on the variation with regional height, the samples from the east having higher tectonic positions. The enormous regional age variation is clearly seen in the Novate granite. The Novate granite from Codera, which is situated 2.4 km to the northeast and 500 m higher than the western Novate granite, has a biotite Rb-Sr age of 21.3 m.y., 3.6 m.y. higher than the age from the southwestern Novate granite which is 17.7 m.y. The two granite samples show two distinct parallel cooling lines.

The interpretation of the monazite U-Pb data from the Novate granite seems difficult, and at first glance, incompatible with the interpretation as cooling ages. As had been mentioned in section II, *2, b*, KÖPPEL and GRÜNENFELDER (1975) report a monazite age of 26.0 m.y. for the granite and 30.5 m.y. for a monazite from an inclusion in the granite, which the authors use as an argument for the interpretation of monazite ages as crystallization ages. In this respect, two additional facts should be discussed: 1) Under the slowly changing conditions of regional metamorphism, mineral ages in resistant rocks can survive temperatures which are much higher than their opening or closing temperatures (ARNOLD and JÄGER, 1965). Those authors were able to show that in an ultrabasic inclusion, the pre-Alpine Rb-Sr age of biotite did survive a metamorphic temperature of at least 400°C, with intermediate and completely rejuvenated cooling ages around the inclusion. The resistivity of the rock against metamorphism seems to be caused by the lack of fluid phases, preventing the minerals from recrystallizing. The monazite age pattern is similar to this Rb-Sr example, whereby the inclusion has an older age than the granite; 2) Data should not be compared from faster magmatic cooling to slower cooling after a metamorphic phase. As had been shown in section II, the blocking temperature is dependent on the cooling rate. In the Bergell, we do know that the first cooling must have been very rapid, certainly much faster than the regional cooling in the other areas. Thus, the U-Pb monazite ages from the Novate granite do not assist the interpretation of U-Pb monazite ages from metamorphic terranes.

In summary, the initial fast uplift rate of $>$ 1 mm/y in the Bergell region has consistently slowed during the past, from 0.7 mm/y 20-15 m.y. ago, 0.4 mm/y about 13 m.y. ago, and an average of 0.2 mm/y over the last 13 m.y.

5) General remarks: The effects of two different types of uplift mechanisms have been found in the Central Alps. In the early stages of cooling, we find the mineral ages to be depedent on the tectonic height, older ages in higher tectonic position. This effect has not been found in the younger mineral ages because the present elevation influences the age result. For example, the muscovite Rb-Sr age of the granite-gneiss from the deep Verampio window is younger than all the muscovite ages with higher tectonic position around the window. But the Rb-Sr age of the biotite is the same as the biotite ages from higher tectonic rocks. This shows that in the early stages of cooling, the updoming of the deep Pennine units to the Ticino culmination is superimposed on the regional uplift pattern.

In the later uplift and cooling stages, the connection to the tectonic position is lost and the uplift proceeds in an unpredictable manner. Also, the association with metamorphic isograds is lost with continuing uplift. Although the youngest Rb-Sr cooling ages are situated in an eccentric area, as compared to the mineral isograds, the older zones of biotite ages around 30 m.y. still show a symmetric arrangement to the metamorphic isograds. This symmetry is completely lost when considering the younger apatite fission-track ages. The more recent uplift is less dependent on the conditions during the metamorphism. As an example, the older fission-track ages (> 10 m.y.) in the Bergell area have no western counterpart. The regional uplift bends and breaks the crust. During the regional uplift period, the great important break in the crust occurs as the Simplon-Centovalli fault. So far we have not been able to detect a differential uplift across the Engadine fault but the fission-track data from this area are few.

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ABSTRACT

The post-Lepontine cooling and uplift history of the Central Alps was determined by two different methods: a) various radiometric ages date the cooling at distinct temperatures - monazite U-Pb at 530°C, muscovite and phengite Rb-Sr at 500°C, muscovite and phengite K-Ar at 350°C, biotite Rb-Sr and biotite K-Ar at 300°C, and apatite fission-track at 120°C; uplift rates can be calculated using those temperatures and assuming the geothermal gradient. b) apatite fission-track ages can be used to determine the uplift rate independent from the geothermal gradient assumption; the observed increase of ages with topographic altitude deflects the uplift of a vertical rock column. As applied to the Central Alps, both methods agree on the uplift history.

In the Central Alps, the following regions had recognizable characteristic uplift histories: the *Gotthard* region had uniform uplift for the past 19 m.y. at about 0.6 mm/y; the *Ticino* area had a continuous decrease in the uplift rate from 1.3 mm/y about 20 m.y. ago to 0.4 mm/y for the last 7 m.y.; the *Bergell* region had even a more pronounced decrease in the uplift rate, from 1 mm/y 25 m.y. ago to 0.2 mm/y for the last 13 m.y. The Bergell intrusion was probably a result of the fast and early uplift. In contrast, the uplift in the western part of the Central Alps has accelerated from 0.3 mm/y to 0.7 mm/y about 6 m.y. ago in the *Monte Rosa* region, and from 0.7 mm/y to 1.1 mm/y about 3 m.y. ago in the *Simplon-Antigorio* region. A present day maximum uplift is observed in the upper Rhone Valley just north of the Simplon area.

ZUSAMMENFASSUNG

Die postlepontinische Abkühl- und Hebungsgeschichte der Zentralalpen wurde auf zwei verschiedene Weisen untersucht. (a) Verschiedene radiometrische Alter datieren die Abkühlung auf unterschiedliche Temperaturen: Monazit U-Pb auf 530°C, Muskovit und Phengit Rb-Sr auf 500°C, Muskovit und Phengit K-Ar auf 350°C, Biotit Rb-Sr und Biotit K-Ar auf 300°C, und Apatitspaltspuren auf 120°C. Aus den Abkühlraten lassen sich unter Annahme eines geothermischen Gradienten Hebungsraten berechnen. (b) Unabhängig davon können Hebungsraten auch direkt aus Apatitspaltspurenaltern abgeleitet werden. Die beobachtete Zunahme dieser Alter mit topographischer Höhe spiegelt die Heraushebung einer vertikalen Gesteinssäule wider. Angewandt auf die Zentralalpen ergeben sich nach beiden Methoden übereinstimmende Hebungsraten.

In den Zentralalpen wurden folgende Gebiete mit charakteristischer Hebungsgeschichte erkannt. Die *Gotthard* Gegend wurde in den vergangenen 19 Ma ziemlich gleichförmig mit rund 0,6 mm/a herausgehoben. Im *Ticino* hat die Hebung stetig von 1,3 mm/a vor 20 Ma auf 0,4 mm/a der letzten 7 Ma abgenommen. Noch stärker war die Verlangsamung der Hebung im *Bergell*, von weit über 1 mm/a vor 25 Ma auf 0,2 mm/a der letzten 13 Ma. Die Bergellintrusion ist wahrscheinlich eine Folge der schnellen und frühen Hebung. Im Westen der Zentralalpen hat sich die Hebung dagegen beschleunigt, von 0,3 mm/a auf 0,7 mm/a vor ungefähr 6 Ma in der *Monte* Rosa Gegend und von 0,7 mm/a auf 1,1 mm/a vor ungefähr 3 Ma in der *Simplon-Antigorio* Gegend. Hier im oberen Rhonetal wird auch heute noch ein Maximum der rezenten Hebung beobachtet.

RÉSUMÉ

L'évolution post-Lepontine du soulèvement et refroidissement des Alpes Centrales est détérminée par deux méthodes différentes:

a): Divers âges radiométriques datent différentes températures de refroidissement: monazite U-Pb sur 530°C, muscovite et phengite Rb-Sr sur 500°C, muscovite et phengite K-Ar sur 350°C, biotite Rb-Sr et biotite K-Ar sur 300°C, et enfin les traces de fission de l'apatite sur 120°C. Supposant le gradient géothermique on peut calculer de ces dates le refroidissement et la vitesse de soulèvement.

b): La méthode traces de fission appliquée à l'apatite donne diréctement la vitesse du soulèvement: l'augmentation des âges corréle avec l'altitude topographique réflécte diréctement la vitesse du soulèvement d'une colonne rocheuse verticale.

Les deux méthodes donnent les mêmes resultats concernant la vitesse de soulèvement dans les Alpes Centrales oû on peut distinguer différentes zones qui sont charactérisées par l'histoire du soulèvement. La région du Gottard montre une vitesse du soulèvement très constante, 0,6 mm/a, depuis les dernièrs 19 m.a.. Au Tessin, la vitesse de soulèvement a diminuée de 1.3 mm/a avant 20 m.a. au 0,4 mm/a pour les dernièrs 7 m.a. Cette diminuation de vitesse de soulèvement est plus prononcée au Bergell, de 1 mm/a avant 25 m.a. sur 0,2 mm/a pour les dernièrs 13 m.a. Probablement, la formation du magma granitique de l'intrusion du Bergell est une conséquence d'un soulèvement très vite au températures hautes. Au contraire, à l'Ouest des Alpes Centrales, la vitesse de soulèvement s'accélerait, de 0.3 mm/a à 0.7 mm/a avant 6 m.a. dans la région de Monte Rosa et de 0.7 mm/a à 1.1 mm/a avant 3 m.a. dans la région du Simplon au Antigorio. Ici, à la vallée du Rhône supérieure on peut observer un maximum de vitesse du soulévement recent.

RIASSUNTO

La storia post-lepontina del sollevamento montuoso e del raffreddamento delle rocce nelle Alpi Centrali è stata determinata con due metodi diversi. A) varie età radiometriche datano il raffreddamento a temperature ben distinte - monazite U-Pb a 530°C, muscovite e fengite Rb-Sr a 500°C, muscovite e fengite K-Ar a 350°C, biotite Rb-Sr e biotite K-Ar a 300°C, ed infine le tracce di fissione dell'apatite a 120°C; i tassi di sollevamento si possono calcolare adoperando queste temperature e presumendo il gradiente geotermico. B) si possono usare le età delle tracce di fissione dell'apatite per determinare il tasso di sollevamento anche indipendentemente dall'assunzione di un gradiente geotermico; il constatato incremento di queste età con l'altitudine topografica rispecchia il sollevamento di una colonna verticale di roccia. Entrambi i metodi concordano per quanto riguarda la storia del sollevamento delle Alpi Centrali.

Nelle stesse Alpi Centrali vennero riconosciute le seguenti regioni con storie caratteristiche di sollevamento: la regione del *Gottardo* subì durante gli ultimi 19 m.a. un sollevamento uniforme di circa 0.6 mm/a; nella regione del *Ticino* il tasso di sollevamento diminuì in continuazione da 1.3 mm/a in atto circa 20 m.a. fa sino a 0.4 mm/a durante gli ultimi 7 m.a.; ancora più pronunciata fu la riduzione del tasso di sollevamento nella regione di *Bregaglia*, da oltre 1 mm/a in atto 25 m.a. fa sino a 0.2 mm/a durante gli ultimi 13 m.a. L'intrusione di Bregaglia fu probabilmente il risultato di un antico e rapido sollevamento. Al contrario, il sollevamento nella parte occidentale delle Alpi Centrali subì un'accelerazione da 0.3 mm/a a 0.7 mm/a circa 6 m.a. fa nella regione del *Monte Rosa*, e da 0.7 mm/a a 1.1 mm/a circa 3 m.a. fa nella regione del *Sempione-Antigorio*. Anche oggi un valore massimo del sollevamento si osserva nella vallata superiore del Rodano, proprio a nord dell'area del Sempione.

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