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The Young Uplift and Thermal History of the Central Eastern Alps (Austria/Italy), Evidence from Apatite Fission Track Ages

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With 13 figures and 2 tables

Ostalpen
Austroalpin
Penninikum
Tauernfenster
Tauernkristallisation
Radiometrische Altersbestimmungen
Apatit-Spaltspurenalter
Urangehalt
Hebungsraten
Abkühlungsgeschichte

Zusammenfassung

Die nach dem Abklingen der alpidischen Regionalmetamorphose (Tauernkristallisation) fortschreitende Hebung und Abkühlung des Tauernfensters und seines austroalpinen Rahmens (zentrale Ostalpen) wurde mit Spaltspurenaltersdatierungen an Apatiten untersucht. Die Apatit-Konzentrate wurden aus Gneisen und Metabasiten separiert. Die Apatit-Spaltspurenalter des Tauernfensters liegen zwischen 5,1±0,5 und 10,5±1,1 Ma (±2s), die seines nördlichen und südlichen austroalpinen Rahmens zwischen 7,0±0,8 und 42±8 Ma (±2s). Eine Probe aus dem südalpinen „granito di Bressanone" (Brixener Granit, 840 m ü. NN) südlich der Insubrischen Linie hat ein Alter von 16,6±2,2 Ma (±2s).

Über angenähert vertikale Probenprofile wurden für ausgewählte Gebiete die folgenden Hebungsraten bestimmt: Granatspitz 0,4 mm/a, Großvenediger 0,4 mm/a, Olperer – Zillertaler Alpen 0,5 mm/a; diese Werte gelten für den Zeitraum zwischen 10 und 5 Ma. Die Hebungsrate des zentralen Tauernfensters war etwas langsamer als die des westlichen. Dieser Unterschied ist auch aus den entsprechenden K/Ar- und Rb/Sr-Glimmerabkühlungsaltern erkennbar.

Als Anomalie in der sonst relativ homogenen Spaltspurenaltersverteilung innerhalb des Tauernfensters treten im Granatspitz gehäuft sehr niedrige Alter auf, obwohl die Hebungsrate hier etwa den gleichen Betrag wie die der Umgebung hatte. Als Erklärung stehen vorerst folgende zwei Modelle zur Diskussion:

1. Es erfolgte im Zeitraum zwischen 5 Ma und jetzt eine isoliert blockartige, schnellere Hebung des Granatspitzmassivs gegenüber seiner Umgebung.
2. Der Geothermische Gradient im Granatspitzmassiv war signifikant höher als in den umgebenden Metabasiten. Die zu vermutende höhere Wärmeproduktion in den Granitgneisen kann durch deren relativ höhere U-, Th- und K-Gehalte verursacht worden sein.

Apatit-Spaltspurenalter von 22,9±3,8 Ma bis 42±8 Ma (±2s) aus der austroalpinen Grauwackenzone sind wahrscheinlich nicht Abkühlungsalter der mittelalpinen Tauernkristallisation (Temperaturmaximum zwischen 50 und 35 Ma) sondern eher als Mischalter bzw. Abkühlungsalter des „Eoalpinen" Ereignisses (Temperaturmaximum zwischen 90 und 80 Ma) zu interpretieren.

Die kontinuierliche Zunahme sowohl der Apatit-Spaltspurenalter als auch der Glimmer-Abkühlungsalter entlang eines West–Ost Profils innerhalb des Tauernfensters spricht gegen die Existenz eines unabhängigen dritten, sog. „Neoalpinen" Metamorphoseereignisses in Form eines Wärmedoms vor etwa 20 Ma.

Summary

The uplift and cooling of the Penninic Tauern Window and of its Austroalpine frame (central Eastern Alps) has continued from the end of the Alpine regional metamorphism until the present day. This postmetamorphic uplift and cooling history was studied by the fission track dating method applied to apatites which were separated from the metamorphic crystalline rocks.

The apatite fission track ages from the Tauern Window and its northern and southern Austroalpine frame (Eastern Alps) range from 5.1±0.5 to 42±8 Ma (±2s); the elevations of the sampling points range from 500 to 3500 m above sealevel. One sample of the Southern Alps, the " granito di Bressanone" (Brixen Granite, 840 m above sea level) south of the Periadriatic Lineament (Insubric Line), gives an age of 16.6±2.2 Ma (±2s).

Sample groups along subvertical profiles from selected areas give the following uplift rates: The Granatspitz area 0.4 mm/a, the Venediger massif 0.4 mm/a, the Zillertaler Alps 0.5 mm/a; these uplift rates are valid for the time span between 10 Ma and 5 Ma before the present. The uplift rate of the central Tauern Window was somewhat slower than that in the western part of the window. These different uplift rates are a long lasting phenomenon; indeed, they can also be deduced from the K/Ar- and Rb/Sr-biotite cooling ages found in the literature. The youngest apatite fission track ages are found in the Granatspitz area. These ages are anomalous with respect to the rather homogeneous cooling pattern found in the wider surroundings, particularly as the early uplift rate of the Granatspitz area is similar to that of the surroundings. Two explanations are possible to account for the young ages of the Granatspitz area:

1. During the time span between 5 Ma and today the uplift of the Granatspitz occurred at a higher rate than the surroundings.
2. The geothermal gradient in the Granatspitz gneiss body was significantly higher than in the surrounding metabasites due to a higher heat production caused by higher U, Th and K contents in the granitic gneisses than in the metabasites.

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Fission track ages of about 22.9±3.8 and 42±8 Ma (±2s) found in the Austroalpine Grauwackenzone can be considered as cooling ages of the Eoalpine event (temperature maximum between 80 and 90 Ma) rather than those of the regional middle Alpine metamorphism (= "Tauernkristallisation", temperature maximum between 35 and 50 Ma).

Evidence from the continuous change of apatite fission track ages and mica cooling ages along an EW profile within the Tauern Window argues against the existence of an independant third Alpine metamorphic event at around 20 Ma.

1. Introduction and problem

The main intention of this paper is to analyse the young uplift and thermal history of the Penninic rocks of the Tauern Window, based on a study of fission track ages from apatites. The investigated area is shown in Fig. 1 on a geological sketch map of the Eastern Alps. The fission track ages of apatites from a low to medium grade regional metamorphic terrain like the Penninic unit in the Eastern Alps are cooling ages (WAGNER, 1968; WAGNER & REIMER, 1972). They give the time elapsed since the rocks were uplifted through a certain isotherm corresponding to the closure temperature of the fission tracks in apatite. The closure temperature is dependent on the cooling rate (NAESER & FAUL, 1969; DODSON, 1979). The slow cooling model (B) according to WAGNER (1979) is typical for regional metamorphic terrains like the Penninic Tauern Window in the Eastern Alps.

In the Central Alps an increase of apatite fission track ages with increasing topographic elevation was observed from which uplift rates between 0.2 and 1.1 mm/a were calculated (WAGNER & REIMER, 1972; WAGNER et al., 1977).

Using the mean geothermal gradient of 30°C/km suggested by SASSI et al. (1974) for the Eastern Alps and by WAGNER et al. (1977) for the Central Alps and using uplift rates from 0.3 to 0.8 mm/a as calculated for the Tauern area by CLARK (1979) on the basis of heat flow data from the Tauern tunnel (Eastern Tauern Window), the closure temperature of fission tracks in apatite for the study area is about 100°C. This corresponds according to DODSON (1979), to a cooling rate between 10°C/Ma and 30°C/Ma.

The closure temperature of Rb/Sr and K/Ar in biotite is about 300°C±50°C (PURDY & JÄGER, 1976; JÄGER, 1979). This closure temperature is obviously closer to the peak temperature of the last metamorphic event than that of the fission tracks in apatite. Therefore, a combination of the apatite fission track ages with the Rb/Sr- and K/Ar-ages of biotite and white mica extends the information on the cooling history to times closer to the metamorphic peak.

The cooling history of a geological unit is influenced by the heat production in the unit itself and by the heat flow from below. Most of the heat produced in the rocks is produced by the decay of natural unstable isotopes of K, U and Th. No data exist on the heat production in the study area.

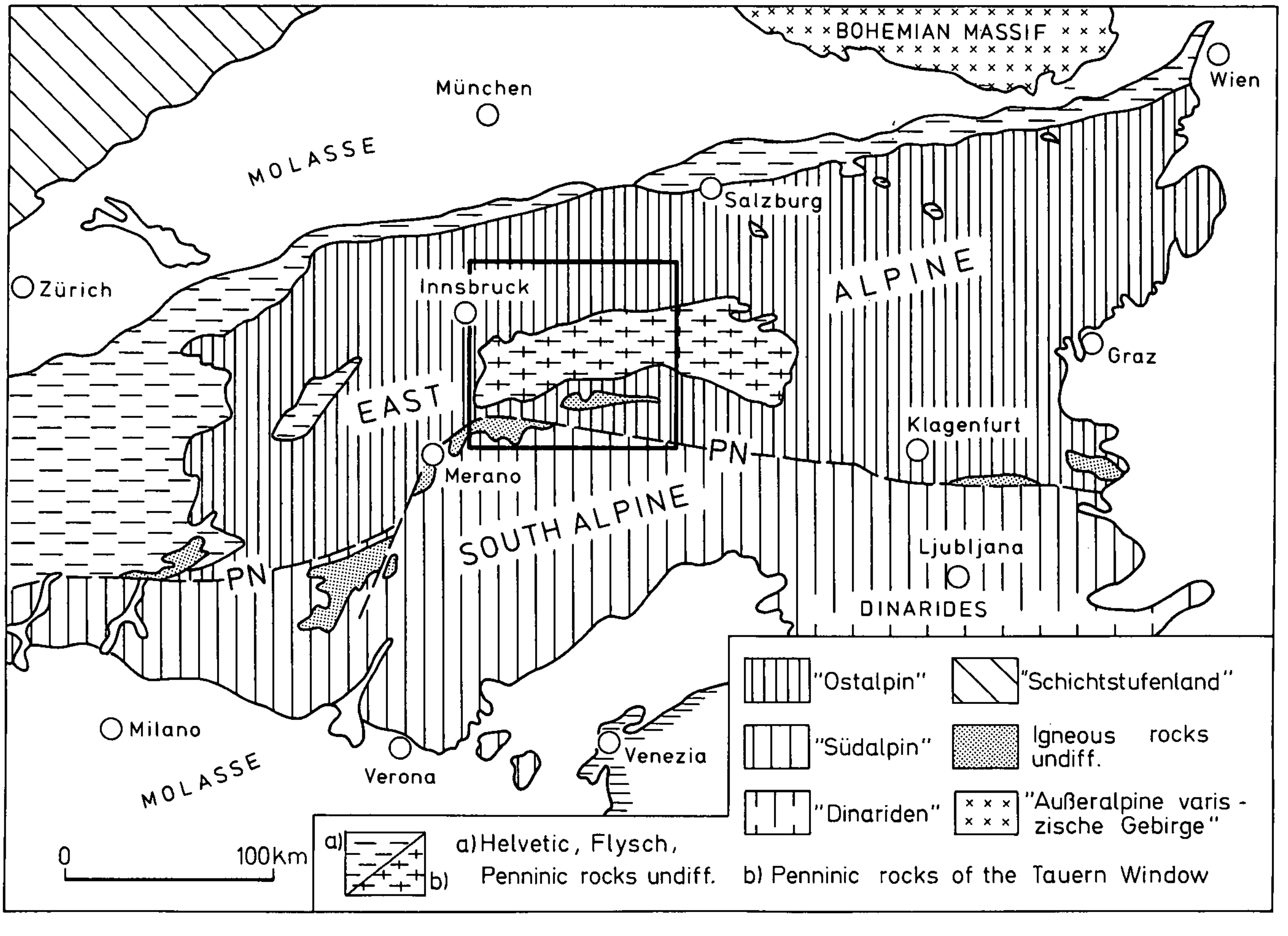

Fig. 1: Geological sketch map of the Eastern Alps. The investigated area is within the frame.

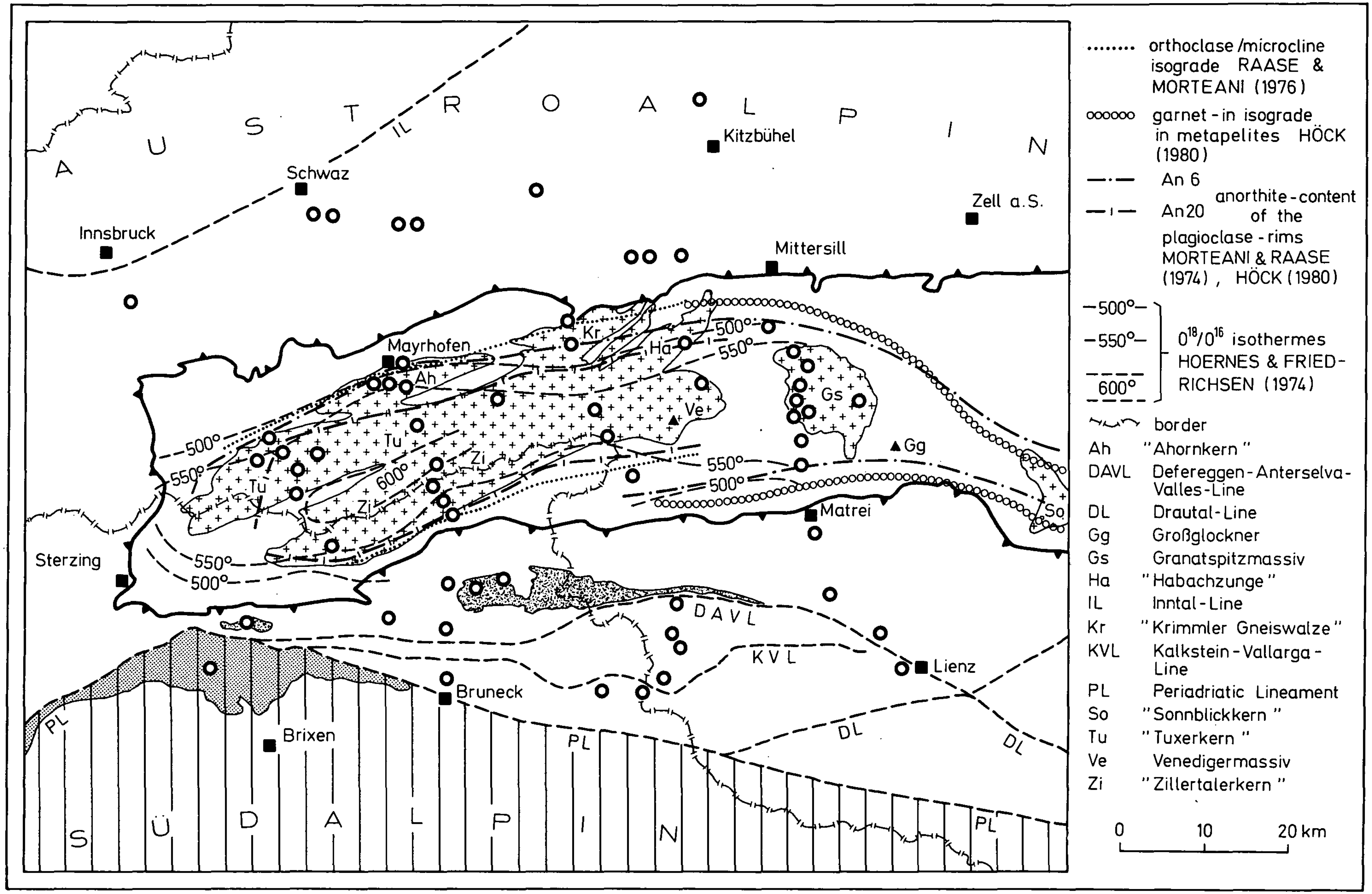

Fig. 2: The isotherms and isograds of the Alpine regional metamorphism ("Tauernkristallisation") within the Tauern Window.
The sampling localities are open dots.

Most of the radiometric ages in the Penninic rocks of the Tauern Window and the Austroalpine units are Rb/Sr or K/Ar ages on biotite and white mica (BESANG et al., 1968; JÄGER et al., 1969; RAITH et al., 1978; SATIR, 1975; BORSI et al., 1973, 1978; DEL MORO, 1982; HAMMERSCHMIDT, 1981; SATIR & MORTEANI, 1979, 1982; CLIFF, 1977).

The most important thermal event in the Penninic rocks of the Tauern Window and in the rocks of the Austroalpine unit near the border of the Tauern Window was the regional middle Alpine metamorphism (the so-called "Tauernkristallisation" of SANDER, 1911, 1921). In the Austroalpine series more distant from the border of the Tauern Window the last regional metamorphic event was early Alpine or Hercynian (see below). KREUZER et al. (1978) discussed the following division of the Alpine metamorphic events: Eo-Alpine event (120–80 Ma), Meso-alpine event (50–30 Ma), Neo-Alpine event (20 Ma). Several authors suggest for the Penninic rocks the existence of a low grade metamorphism younger than the middle Alpine Tauernkristallisation (BORSI et al., 1973; SASSI et al., 1974, 1980; RAITH et al., 1978). According to RAITH et al. (1978), the "early alpidic phase" of high pressure/low temperature conditions ranges from 70–50 Ma; the middle Alpine Tauernkristallisation, a Barrovian metamorphism, is called "main Alpidic event" and probably took place in the time-span between 50 and 30 Ma; the younger event is called "latest post-kinematic crystallization representing the last climax of the alpidic metamorphism" and took place at around 20 Ma. BORSI et al. (1973) and SASSI et al. (1974, 1980) also suggest the existence of a low grade metamorphism younger than the Tauernkristallisation, a "third Alpine metamorphic event" at around 20 Ma.

The thermal conditions and areal distribution of the metamorphic grade of the middle Alpine Tauernkristallisation in the Penninic rocks are known from e. g. the studies of HOERNES (1973), HOERNES & FRIEDRICHSEN (1974), RAASE & MORTEANI (1976), HÖCK & HOSCHEK (1980), SATIR & FRIEDRICHSEN (1983) and SELVERSTONE et al. (1984). In Fig. 2 the isotherms and isograds of the middle Alpine Tauernkristallisation in the Tauern Window are given according to MORTEANI & RAASE (1974), HOERNES & FRIEDRICHSEN (1974), RAASE & MORTEANI (1976) and HÖCK (1980). They are roughly parallel to the border of the Tauern Window.

The metamorphism in the Austroalpine units north and south of the Tauern Window has been studied by e.g. SCHRAMM (1978, 1980), ACKERMAND & MORTEANI (1977), BORSI et al. (1973, 1980), HOSCHECK (1980), CONTINI & SASSI (1980) and HAMMERSCHMIDT (1981).

Radiometric age determinations on the polymetamorphic Austroalpine rocks north of the Tauern Window and from the Mesozoic sediments which cover them also suggest a Mid-Cretaceous Eoalpine metamorphic event in these units before 90 Ma (HAWKESWORTH et al., 1975; SATIR & MORTEANI, 1979; FAUPL et al., 1980; BERAN et al., 1981; SCHARBERT, 1981; THÖNI, 1983; KRALIK, 1983; FRANK, 1983).

In the Austroalpine unit south of the western and central Tauern Window K/Ar and Rb/Sr cooling ages are given by BORSI et al. (1978), HOSCHEK et al. (1980), SATIR (1975) and HAMMERSCHMIDT (1981). Mica cooling ages from the Austroalpine unit north of the Tauern Window are published by SATIR & MORTEANI (1979).

2. Sampling and Analytical Techniques

The sampled area covers the western and central Tauern Window as well as its northern and southern Austroalpine frame i. e. the Grauwackenzone, the Innsbrucker Quarzphyllit in Austria and the Merano-Mules-Anterselva zone in Italy, this latter zone being a part of the larger Austroalpine "Altkristallin" unit. South of the Periadriatic Lineament (Insubric Line) two samples have been taken from the Brixen Granite (Granito di Bressanone). As shown in Fig. 2 the whole area is limited roughly by the towns of Innsbruck, Kitzbühel, Lienz (all in Austria) and Brixen/Bressanone (Italy). The area covered is about 10,000 square km. Fig. 3 shows the sampling localities and the sample numbers on a simplified geological sketch map.

For this investigation a total of 105 rock samples were collected; from this batch 43 samples turned out to be unsuitable, being too poor in apatite or containing apatites with very low uranium content (<1 ppm U). The sample weight in all cases varied between 3 and 5 kg.

10 samples from the Austroalpine unit north of the Tauern Window, 34 from the Penninic rocks inside the Tauern Window and 18 from the Austroalpine unit south of the Tauern Window could be used for dating. The apatite concentrates were obtained primarily from granitic augengneisses and also from tonalitic gneisses, biotite-plagioclase-gneisses and metabasic rocks. A list of the studied samples including petrographic descriptions and details of the sampling localities is available from the authors on request. The elevations of the sampling localities are between 500 and 3450 m above sea level.

The apatite crystals for the fission track dating were separated from the crushed and ground rock samples using heavy liquids (tetrabromethane) and magnetic separators. The apatite concentrate obtained by these methods was purified by hand picking under the stereo microscope. For dating it was necessary to separate from each rock sample some hundred up to several thousand apatite grains. The pure apatite concentrate was divided in two halves; one half was then heated in air in an electric furnace for 24 h. at 550°C. Later the annealed and the untreated halves of the apatite samples were embedded separately in epoxy pills. The annealed samples were irradiated in the thermal column of the reactor BER II at the Hahn-Meitner-Institut für Kernforschung in Berlin-West. The reactor has a power of 5 megawatt; the neutron flux density inside the thermal column is around 1×10^{10} (neutrons) $\times$ sec^{-1} $\times$ cm^{-2}. The ratio of epithermal to total thermal neutrons was less than 1 : 100. The neutron dose was monitored by Al wires containing 1.000 %, 0.123 % and 0.501 % Co as a monitor. The determination of the activity of the Co monitor after irradiation was made by a multichannel analyser. For the determination of the neutron dose the sum coincidence method of SCHLEY was used. The reliability of the neutron dose determination was checked by comparison with results obtained by WAGNER (Max Planck Institut, Heidelberg; personal communication) on moldavite standards. The irradiated and the untreated samples were etched together in 5 % HNO_3 (corresponding to 140 ml 65 % HNO_3 mixed with 1680 ml H_2O dest.) for 45 sec. at a temperature of 21°C. Counting of the fission tracks was done by microscope (objective: oil immersion 100 ×; oculars 8 ×)

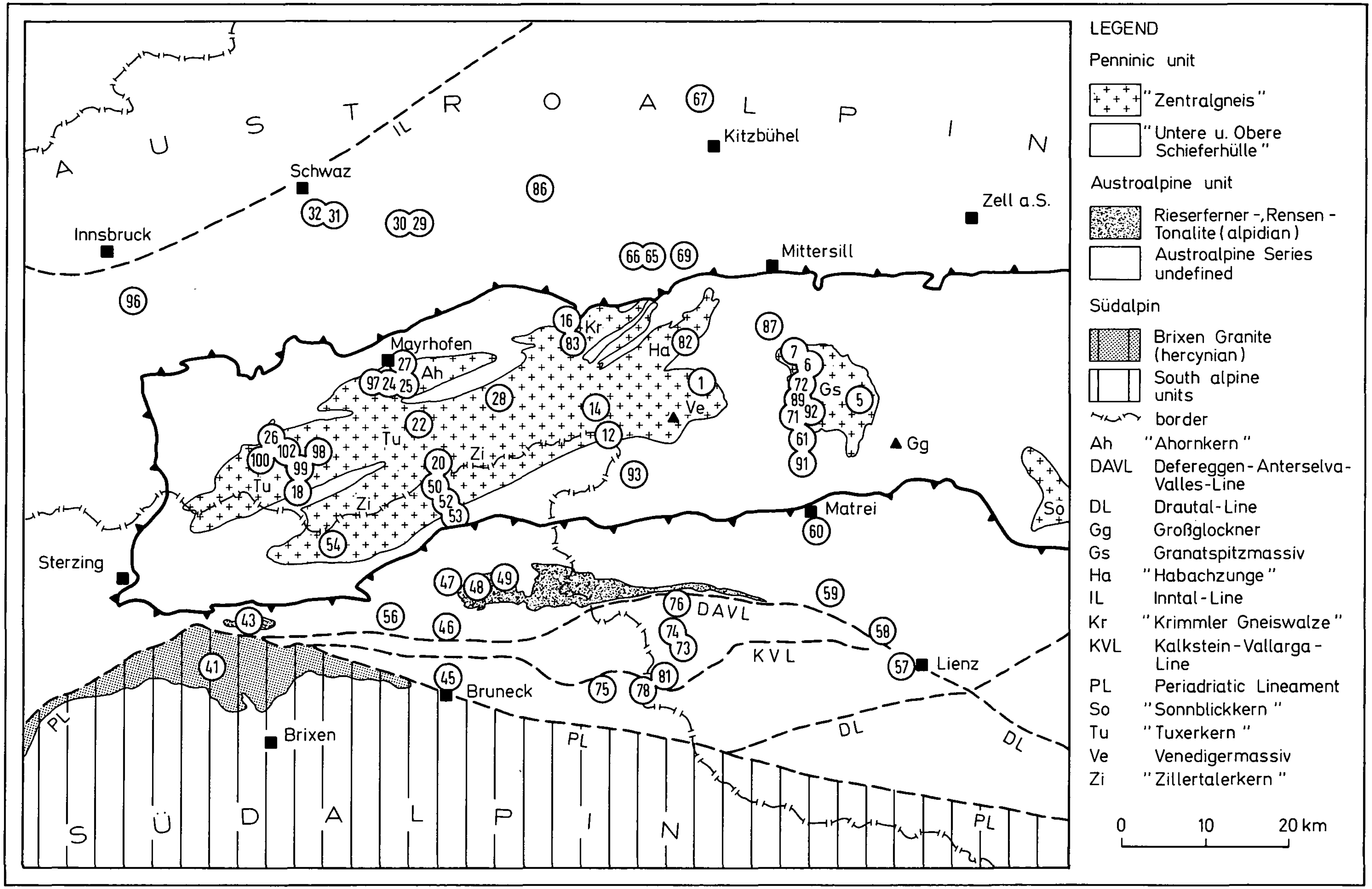

Fig. 3: Sampling localities and sampling numbers presented in a simplified geological sketch map.

using two different counting nets of 10,000 square microns and 1,000 square microns respectively.

3. Results

The analytical data of the fission track dating are given in Tab. 1. The layout of this table is according to the suggestion of NAESER et al. (1979). The fission track ages of the apatites were calculated according to the formula (1):

$$T = \frac{ps}{pi} \cdot \frac{I \cdot \sigma \cdot D}{\lambda_f} = \frac{ps}{pi} \cdot D \cdot \text{const.} \quad (1)$$

The symbols mean:
ps = number of spontaneous fission tracks per cm^2
pi = number of induced fission tracks per cm^2
I = ratio of the isotopes $^{235}U/^{238}U = 7.2527 \cdot 10^{-3}$
σ = neutron capture cross section = 580.2 barn
D = number of thermal neutrons per cm^2
λ_f = decay constant = $8.46 \cdot 10^{-17} \cdot a^{-1}$
T = fission track age, i. e. the time span between the cooling of the apatite below 100°C, given in millions of years.

For the calculations the decay constant

$$f = 8.46 \cdot 10^{-17} \cdot a^{-1}$$

(GALLIKER et al., 1970) was used. The errors are given in Tab. 1 according to the suggestion of NAESER et al. (1979).

The regional distribution of the measured fission track ages is given in Fig. 4. The youngest ages appear along the central axis of the Tauern Window. The oldest ages are found in the areas of the Austroalpine domain farthest from the border of the Penninic Tauern Window. A rather old age is also shown by the sample from the Brixen Granite (sample No. 41) in the Southern Alps south of the Insubric Line.

The fission track ages of samples originating from a more or less vertical profile can be used for a direct determination of the uplift rate. This uplift rate is only valid for the time span covered by the fission track ages used. In Fig. 5 the elevation of the sampling points (meters above sea level) is plotted against the corresponding fission track ages. The heavy lines are the least squares linear regression lines calculated for selected areas. The slope of the regression lines gives the uplift rate in meters per million years. The numbers near the lines give the resulting uplift rates in millimeters per year.

The areas of the Granatspitz, Krimmler Achental and of the Habachtal show similar uplift rates of 0.4 mm/a. The area between the Schlegeistal and the Stilluptal shows a rate of 0.5 mm/a.

Outside the Tauern window, in the areas of Campo Tures, the Arntal and the Kellerjoch only a few samples are available for the construction of the regression lines. Because of the relatively small differences in elevation covered by the sampling and the rather large scatter of the data points along the regression lines the calculated uplift rates of these areas should be interpreted with care; they are: Campo Tures 0.5 mm/a, Arntal 0.25 mmm/a, Kellerjoch 0.2 mm/a.

At present no information exists on the depth of the recent 100°C isotherm in the studied area. The heavy regression lines, as given for the different areas in Fig. 5, can be linearly extrapolated to the time zero (dashed lines) i. e. to the present time. The intercept of the extrapolated lines with the y-axis defines the level of the present 100°C isotherm provided that the closure temperature of the fission tracks in apatite is around 100°C. It must be pointed out, however, that the linear extrapolation is only valid if the uplift rate remained the same for all different areas starting from the oldest fission track ages determined up the present. For the areas of the Krimmler Achental, the Habachtal and the Stilluptal a depth of about 2000 m below sea level is defined by the regression lines, whereas for the areas of the Arntal, the Kellerjoch and the Granatspitz the 100°C isotherm is at a depth of only about 1000 m below sea level. A linear extrapolation of the data from Campo Tures and Steinkogel gives a depth of much more than 2000m below sea level for the 100°C isotherm.

As mentioned above, the fission track ages increase with increasing elevation of the sampling points. For a discussion of the regional uplift pattern one has to refer therefore to a common elevation. In agreement with the suggestion of WAGNER et al. (1977) a reference elevation of 1000 m above sea level was chosen. The intersection of the regression line (showing the uplift rate) with the line at 1000 m above sea level gives the time at which sample groups of identical uplift rate passed through the 100°C isotherm (Fig. 5) provided that the 100°C isotherm was horizontal over the entire study area.

In Fig. 6 the areal distribution of the fission track ages after reduction to the 1000 m reference elevation is given. The sample groups are the same as those used for the determination of the direct uplift rates (see above). The time intervals are: 0–5, 5–6.5, 6.5–8, 8–11 and older than 11 Ma. This figure shows that the youngest ages are found along the central axis of the E–W-trending Penninic Tauern Window. Starting from this axis to the north and to the south increasingly older ages appear.

Clear age differences between the areas north and south of the important tectonic lines south of the Tauern window (e. g. the DAV-and the Periadriatic lines) have been observed from Rb/Sr and K/Ar mica ages by BORSI et al. (1978). By contrast no general age discontinuities can be demonstrated from the fission track ages across the DAV- and the KV-lines. This may be due to

a) small number of samples
 and/or
b) rather small age differences along the tectonic lines
 or
c) the fact that vertical movements along the tectonic lines are older than the fission track ages but younger than the Rb/Sr and the K/Ar mica ages.

Large age differences are shown only by the samples 57 and 58 (near Lienz) as well as by the samples 41 and 43 (between Brixen and Sterzing). In Fig. 7 the uranium contents of the apatites are shown as calculated from the induced fission tracks according to the formula (2):

$$U = \frac{p}{D \cdot F} \quad (2)$$

The symbols mean:
U = Uranium content in ppm
p = number of induced fission tracks per cm^2
D = number of thermal neutrons per cm^2
F = factor – valid for fission tracks in apatite etched 45 sec. in 5 % HNO

Table 1: Fission track data table.

	(1) Sample code	(2) elevation above sea level	(3) ρ_s		(4) ρ_s $\overline{s}$	(5) ρ_s $\overline{sp}$	(6) ρ_i		(7) ρ_i $\overline{s}$	(8) ρ_i $\overline{sp}$	(9) ρ_s/ρ_i	(10) Neutron dose	(11) Error of of neutron dose	(12) Factor 2s	(13) Age	(14) Error of age	(15) Number of grains or fields	(16) field size	(17) Apatite
		[m]	[x10^5 tracks/cm^2]	[tracks]	[%]	[%]	[x10^5 tracks/cm^2]	[tracks]	[%]	[%]		[x10^{15} neutrons/cm^2]	[%]		[Ma]	±2s [Ma]		[mm^2]	U [ppm]
1	SP 79.1	1920	0.33	100	12.35	10.00	1.06	317	9.27	5.62	0.315	6.045	2.0	0.2328	9.5	2.2	300/300	0.001	6.4
2	SP 79.5	2300	1.05	525	6.09	4.36	7.93	3964	4.04	1.58	0.132	11.25	3.0	0.1106	7.4	0.8	500/500	0.001	26
3	SP 79.6	1700	1.08	425	4.88	4.85	7.68	3070	2.75	1.81	0.139	8.75	3.0	0.1196	6.0	0.7	400/400	0.001	32
4	SP 79.7	1450	1.32	661	5.51	5.20	14.47	7234	2.44	1.47	0.091	11.26	3.0	0.1010	5.1	0.5	500/500	0.001	47
5	SP 79.12	1890	0.36	108	9.60	9.62	1.35	405	7.24	4.97	0.267	6.840	3.0	0.2248	9.1	2.0	300/300	0.001	7.2
6	SP 79.14	1650	0.58	175	8.35	7.56	2.29	688	5.65	3.81	0.254	6.672	3.0	0.1796	8.5	1.5	300/300	0.001	13
7	SP 79.16	1170	0.54	162	8.17	7.86	1.65	495	6.80	4.49	0.327	6.379	3.0	0.1810	10.4	2.0	300/300	0.001	9.4
8	SP 79.18	1790	0.59	176	8.10	4.42	2.34	701	5.18	3.80	0.251	5.948	3.0	0.1790	7.5	1.1	300/300	0.001	14
9	SP 79.20	1840	0.88	264	7.25	6.15	3.40	1019	4.50	3.13	0.259	5.658	1.9	0.1433	7.3	1.2	300/300	0.001	22
10	SP 79.22	1300	0.60	181	8.17	7.43	4.74	1423	5.24	2.60	0.127	10.76	3.0	0.1689	6.7	1.1	300/300	0.001	16
11	SP 79.24	1000	0.83	250	6.51	6.30	7.34	2203	3.62	2.13	0.113	10.82	3.0	0.1463	6.1	0.9	300/300	0.001	25
12	SP 79.25	2070	1.26	377	6.87	5.14	7.43	2230	5.18	2.12	0.169	9.588	3.0	0.1265	8.1	1.0	300/300	0.001	28
13	SP 79.26	2630	0.91	273	6.44	5.95	2.88	863	4.41	3.40	0.316	5.658	3.0	0.1435	9.2	1.3	300/300	0.001	19
14	SP 79.27	750	1.08	325	5.35	5.55	2.51	752	5.77	3.65	0.432	4.127	3.0	0.1387	8.9	1.2	300/300	0.001	22
15	SP 79.28	1600	0.50	149	7.75	8.19	1.83	548	5.94	4.27	0.272	5.620	1.7	0.1879	7.6	1.4	300/300	0.001	12
16	SP 79.29	510	1.02	406	7.44	4.97	2.02	806	5.27	3.52	0.504	3.808	2.3	0.1301	9.6	1.2	400/400	0.001	19
17	SP 79.30	530	0.86	259	6.82	6.21	1.82	546	5.77	4.28	0.474	3.859	2.3	0.1578	9.1	1.4	300/300	0.001	17
18	SP 79.31	2030	4.70	1411	5.15	2.66	5.19	1558	5.42	2.53	0.906	3.895	2.2	0.0857	17.6	1.5	300/300	0.001	49
19	SP 79.32	1330	1.08	430	12.11	4.82	2.40	959	11.14	3.23	0.448	6.491	3.7	0.1377	14.5	2.0	400/400	0.001	14
20	SP 79.41	840	0.75	376	4.86	5.14	2.43	1213	3.70	2.86	0.310	10.72	3.0	0.1324	16.6	2.2	500/500	0.001	8.3
21	SP 79.43	1450	0.25	74	11.62	11.62	0.62	187	7.28	7.31	0.396	3.937	2.5	0.2792	7.8	2.2	300/300	0.001	5.7
22	SP 79.45	880	0.61	245	7.60	6.38	1.30	521	5.34	4.40	0.470	3.899	2.1	0.1600	9.2	1.5	400/400	0.001	12
23	SP 79.46	950	0.73	219	9.52	6.76	1.50	450	7.76	4.71	0.487	3.491	2.4	0.1716	8.5	1.5	300/300	0.001	16
24	SP 79.47	910	0.65	261	6.52	6.19	3.84	1536	4.15	2.55	0.170	10.21	3.0	0.1467	8.6	1.3	400/400	0.001	14
25	SP 79.48	1150	0.64	257	6.27	6.24	1.35	541	4.40	4.30	0.475	3.727	2.7	0.1609	8.8	1.4	400/400	0.001	13
26	SP 79.49	1550	0.53	213	7.31	7.93	2.78	1111	3.54	3.47	0.192	10.12	3.0	0.1612	9.7	1.6	400/400	0.001	10
27	SP 79.50	2500	0.65	327	5.76	5.53	2.93	1466	3.79	2.61	0.223	8.10	3.0	0.1362	9.0	1.2	500/500	0.001	13
28	SP 79.52	1440	0.43	130	8.64	8.77	1.08	323	6.93	5.56	0.402	3.623	2.3	0.2128	7.3	1.6	300/300	0.001	11
29	SP 79.53	1050	0.51	204	7.44	7.00	2.00	801	5.04	3.53	0.255	6.457	3.3	0.1702	8.2	1.4	400/400	0.001	11
30	SP 79.54	2000	0.45	135	9.03	8.61	1.95	586	5.47	4.13	0.230	6.503	4.2	0.2086	7.5	1.6	300/300	0.001	11
31	SP 79.56	1200	0.89	266	7.03	6.13	2.95	885	4.96	3.36	0.301	6.057	2.0	0.1455	9.1	1.3	300/300	0.001	18
32	SP 79.57	700	1.21	484	6.20	4.55	2.11	844	5.33	3.44	0.573	3.809	2.7	0.1262	10.9	1.4	400/400	0.001	20
33	SP 79.58	950	0.44	175	7.51	7.56	0.78	311	6.72	5.67	0.563	3.36	2.2	0.1940	9.4	1.8	400/400	0.001	8.5
34	SP 79.59	850	0.32	127	8.22	8.87	0.57	226	6.45	6.65	0.562	3.499	2.2	0.2261	9.8	2.2	400/400	0.001	5.9
35	SP 79.60	920	0.09	568	4.40	4.20	0.51	3030	2.47	1.82	0.187	7.272	3.0	0.1094	7.0	0.8	600/600	0.01	2.6
36	SP 79.61	1500	2.77	1108	3.54	3.00	20.87	8348	2.81	1.09	0.133	10.33	3.0	0.0877	6.8	0.6	400/400	0.001	74
37	SP 80.65	2000	2.26	678	6.51	3.84	5.16	1547	6.06	2.54	0.438	6.153	1.8	0.0989	13.4	1.3	300/300	0.001	31
38	SP 80.66	2000	3.18	955	6.10	3.23	6.67	2001	5.55	2.22	0.477	6.069	2.0	0.0882	14.4	1.3	300/300	0.001	40
39	SP 80.67	800	0.49	244	6.59	6.37	0.37	184	7.31	7.37	1.326	6.414	3.0	0.2043	42	8	500/500	0.001	2.1
40	SP 80.69	1600	0.10	292	8.80	5.85	0.22	667	9.60	3.87	0.438	5.994	3.0	0.1526	13.1	2.0	300/300	0.01	1.3
41	SP 81.71	1560	1.10	441	4.74	4.39	4.10	1622	3.02	2.48	0.272	3.837	2.3	0.1168	6.1	0.7	400/400	0.001	39
42	SP 81.72	1570	1.07	426	5.08	4.81	3.68	1473	3.32	2.61	0.294	3.926	2.1	0.1172	5.7	0.7	400/400	0.001	34
43	SP 81.73	2070	0.95	284	7.03	5.93	1.97	590	5.77	4.12	0.481	6.051	2.1	0.1504	14.5	2.2	300/300	0.001	12
44	SP 81.74	2070	0.73	218	8.74	6.77	1.47	442	6.94	4.75	0.493	5.705	1.9	0.1698	14.0	2.4	300/300	0.001	9.4
45	SP 81.75	2100	1.08	323	7.27	5.56	1.78	535	7.89	4.32	0.604	6.179	2.1	0.1471	18.6	2.7	300/300	0.001	11
46	SP 81.76	1700	1.36	407	5.04	4.96	3.23	968	4.35	3.20	0.417	6.006	3.0	0.1324	12.6	1.7	300/300	0.001	20
47	SP 81.78	2300	1.17	351	9.31	5.34	1.61	483	8.57	4.55	0.727	5.661	3.0	0.1526	20.5	3.1	300/300	0.001	10
48	SP 81.81	1700	0.48	1345	3.37	2.73	0.79	2378	3.15	2.05	0.566	5.505	1.6	0.0754	15.5	1.7	300/300	0.01	5.2
49	SP 81.82	1520	0.71	212	7.01	6.87	2.75	825	4.32	3.48	0.257	6.56	3.1	0.1660	8.4	1.4	300/300	0.001	15
50	SP 81.83	1500	0.52	156	8.49	8.01	2.14	642	5.66	3.95	0.243	6.476	3.8	0.1940	7.8	1.5	300/300	0.001	12
51	SP 81.86	1750	0.97	291	7.00	5.86	1.25	374	6.71	5.17	0.778	5.911	3.0	0.1675	22.9	3.8	300/300	0.001	7.7
52	SP 81.87	1250	0.60	299	6.10	5.78	2.30	1151	3.94	2.95	0.260	6.140	4.2	0.1546	7.9	1.2	500/500	0.001	14
53	SP 81.89	1565	1.51	602	4.51	4.08	7.41	2962	2.68	1.84	0.203	6.319	3.0	0.1077	6.4	0.7	400/400	0.001	43
54	SP 81.91	1300	0.54	163	8.16	7.83	2.58	773	6.90	3.60	0.211	6.578	3.0	0.1825	6.9	1.3	300/300	0.001	14
55	SP 81.92	2430	1.82	726	4.10	3.71	7.27	2907	2.93	1.85	0.250	6.424	3.0	0.1024	8.0	0.8	400/400	0.001	41
56	SP 81.93	2500	1.13	339	5.45	5.43	3.58	1074	4.08	3.05	0.316	6.543	3.0	0.1383	10.3	1.4	300/300	0.001	20
57	SP 81.96	2240	0.57	172	7.80	7.62	1.21	364	5.00	5.24	0.473	6.064	3.0	0.1945	14.3	2.8	300/300	0.001	7.3
58	SP 81.97	800	0.84	251	6.15	6.31	4.89	1467	2.86	2.61	0.171	6.432	3.0	0.1492	5.5	0.8	300/300	0.001	28
59	SP 81.98	1360	0.22	65	12.98	12.40	1.09	326	8.10	5.54	0.199	6.452	3.0	0.2782	6.4	1.8	300/300	0.001	6.2
60	SP 81.99	1650	0.20	79	12.38	11.25	0.89	354	8.76	5.31	0.223	6.277	3.8	0.2602	7.0	1.8	400/400	0.001	5.2
61	SP 81.100	3470	0.27	1075	6.11	3.05	0.90	3605	5.71	1.66	0.298	7.065	3.6	0.1001	10.5	1.1	400/400	0.01	4.6
62	SP 81.102	1800	0.36	109	12.17	9.58	1.49	447	9.17	4.66	0.237	6.356	4.1	0.2283	7.7	1.7	300/300	0.001	8.6

(12) was calculated with: $2 \cdot \sqrt{\frac{1}{\rho_s} + \frac{1}{\rho_i} + (\text{error of neutron dose})^2}$

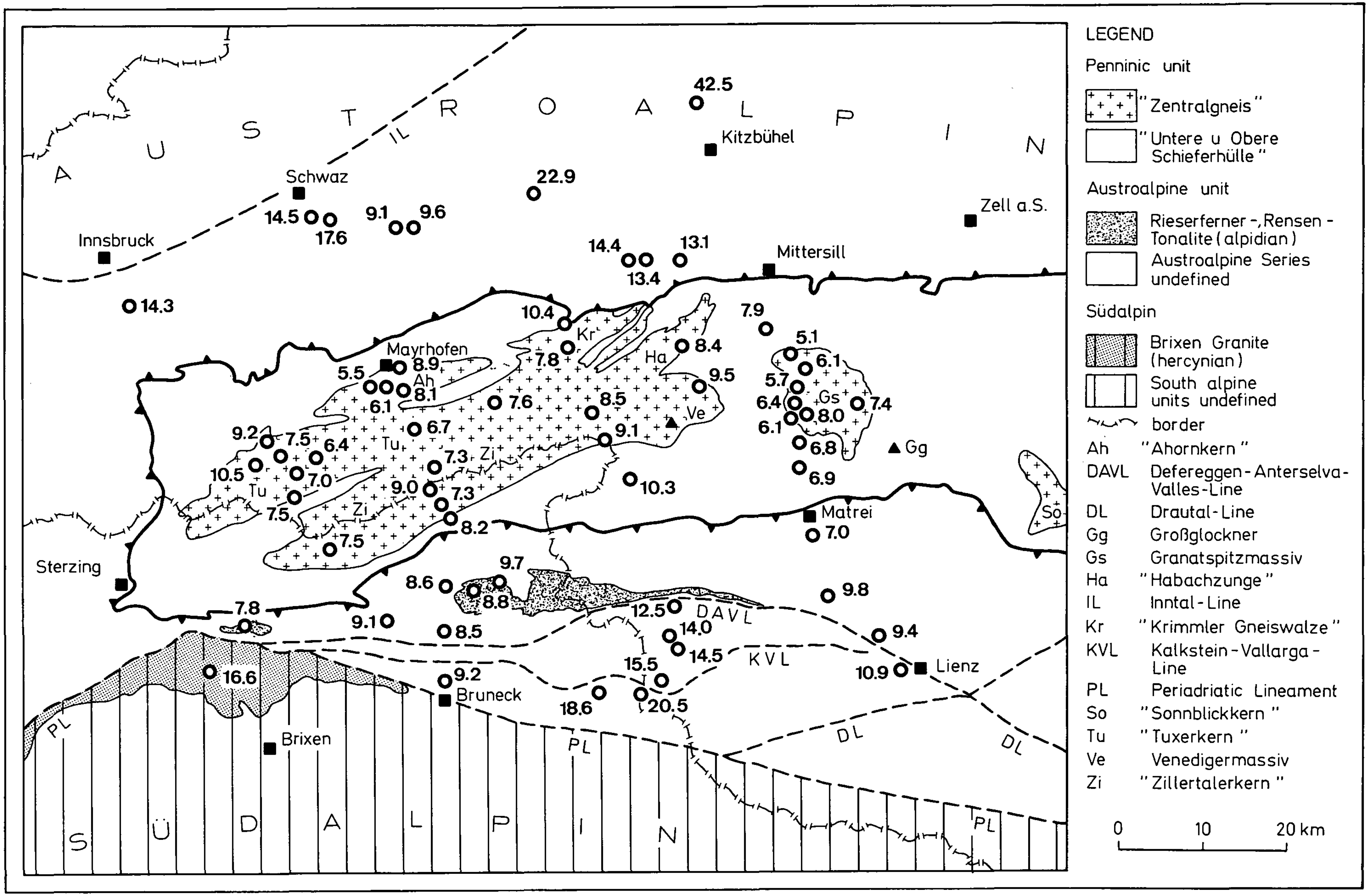

Fig. 4: Regional distribution of the apatite fission track ages measured.

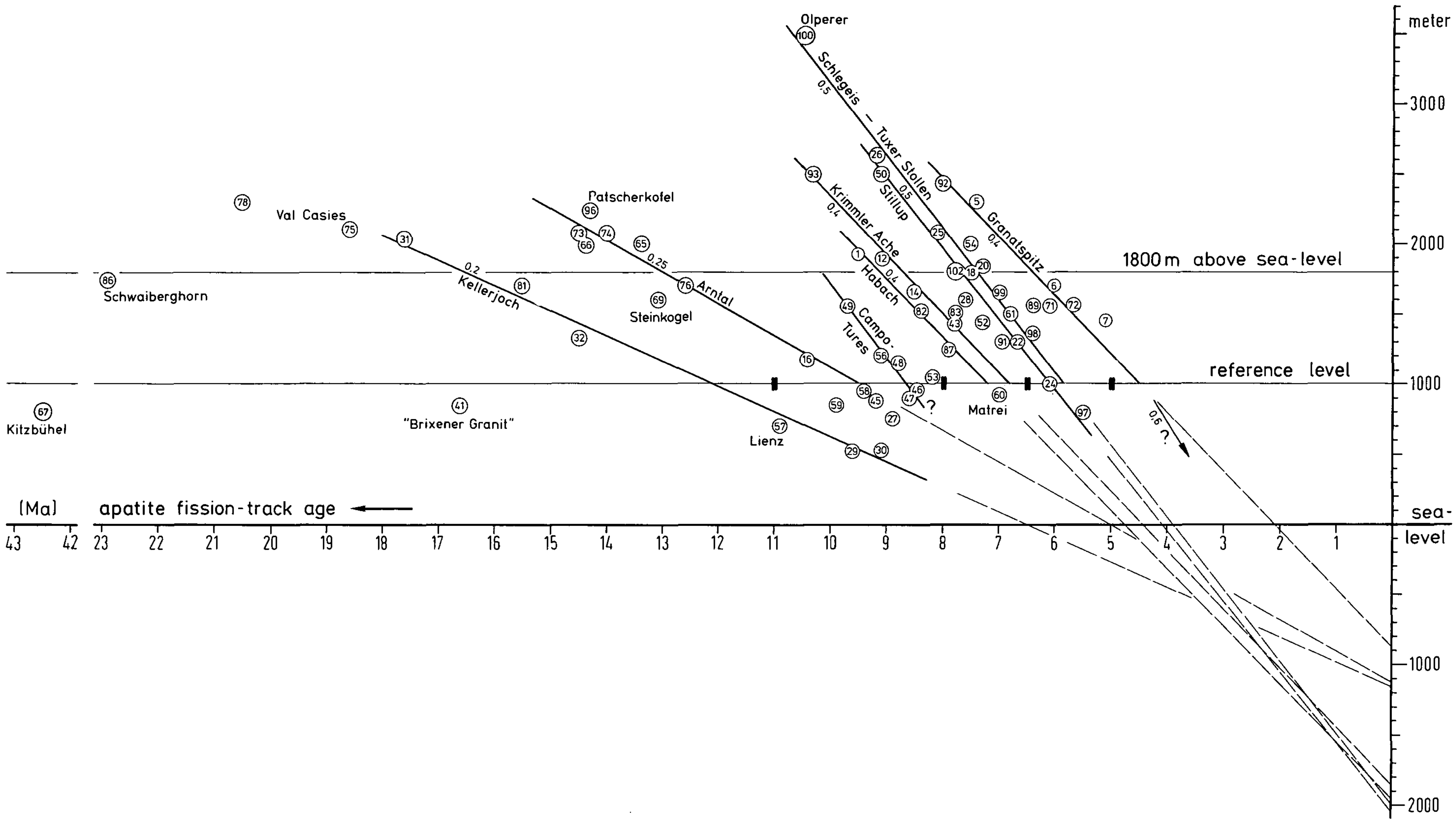

Fig. 5: Elevation of the sampling points versus the corresponding apatite fission track ages. The heavy lines are regression lines giving the uplift rate (in mm/year) for selected areas. The dashed lines are the linear extrapolation of the regression lines. Sample numbers are circled. Black symbols on the reference level give the time intervals referred to in the text.

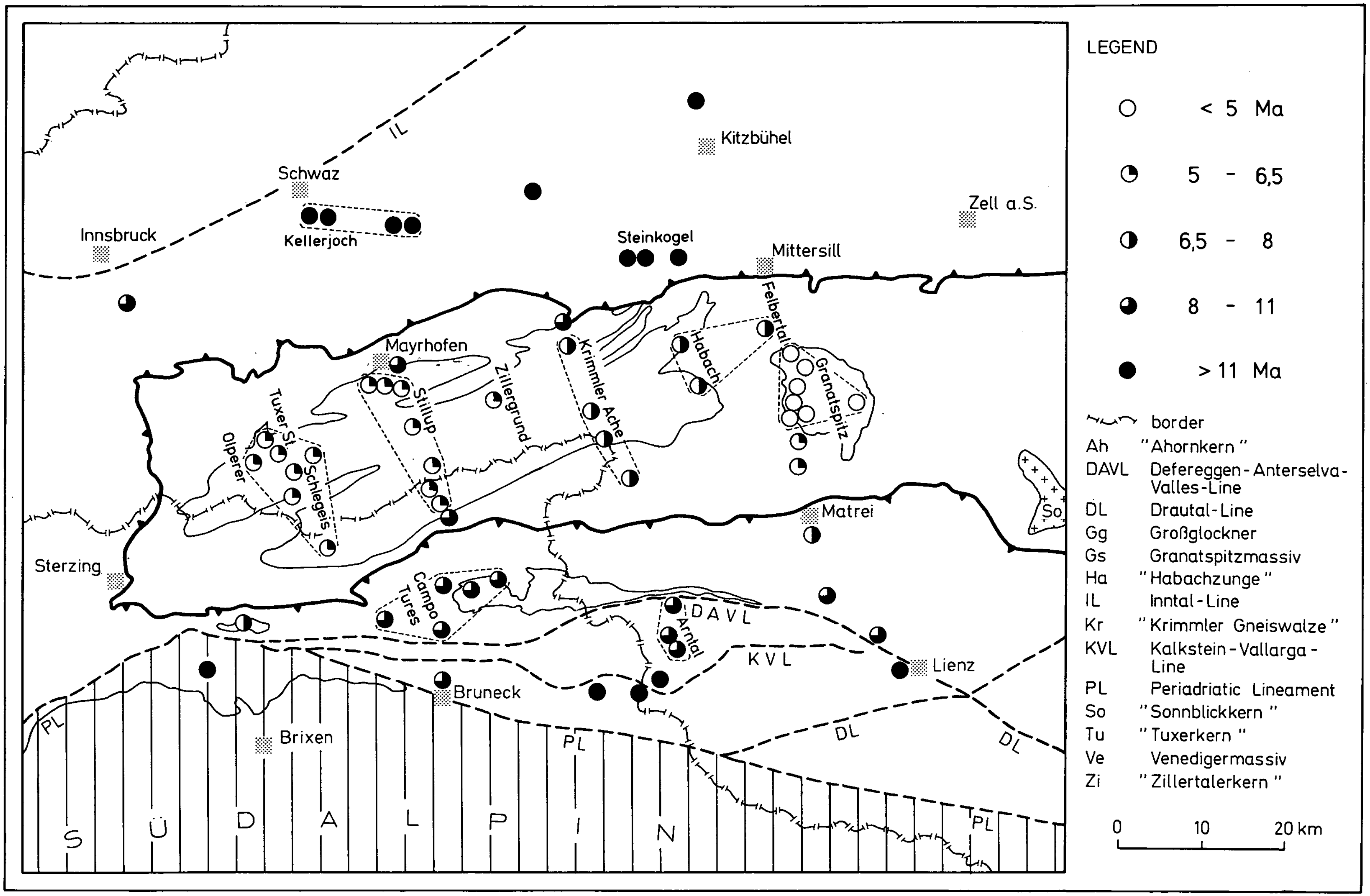

Fig. 6: The areal distribution of the fission track ages after reduction to a reference level of the 1000 m above sea level.

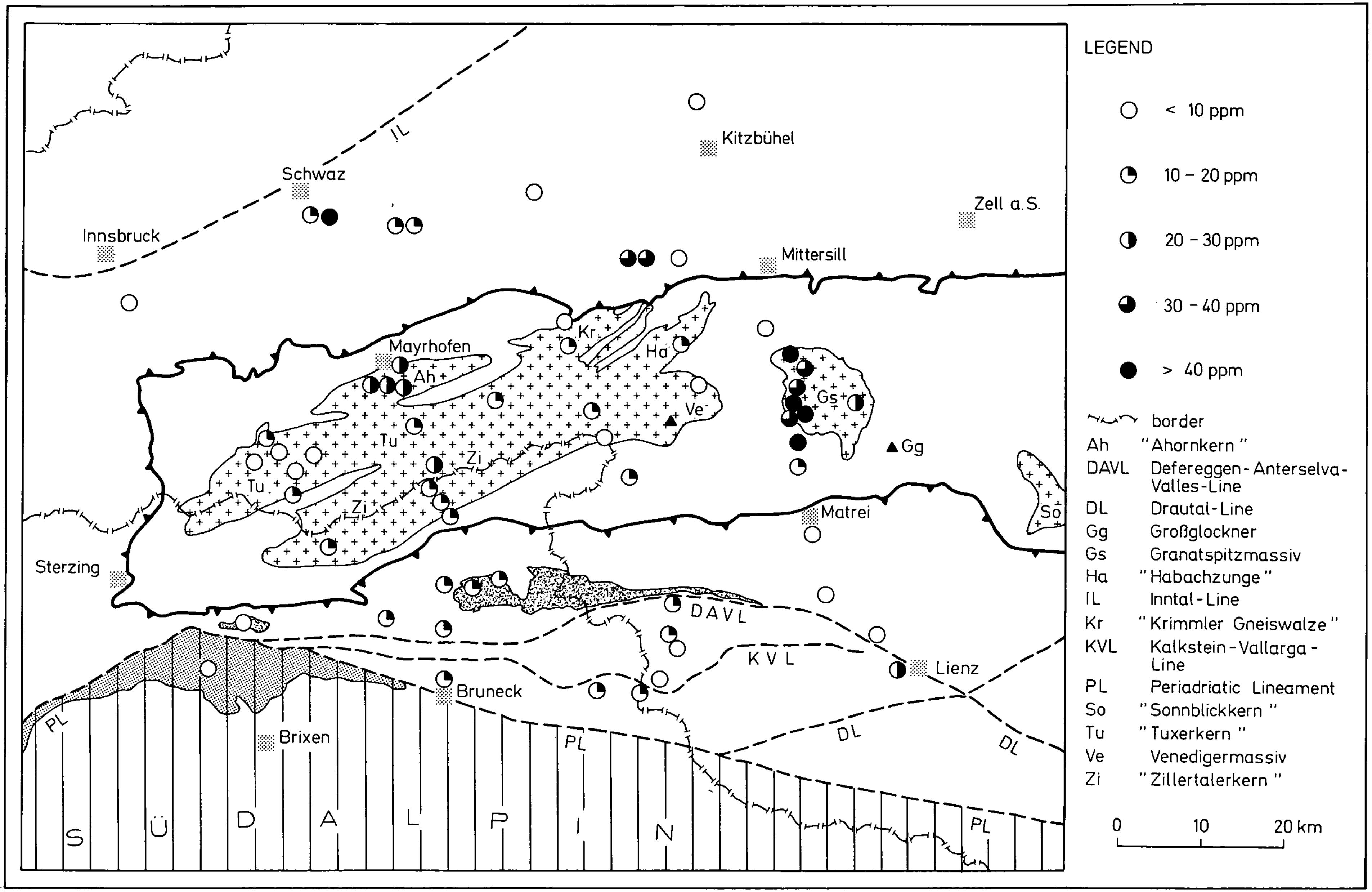

Fig. 7: The regional distribution of the uranium content in apatites from the Penninic rocks of the Tauern Window and from the Austroalpine rocks.

This formula is according to STORZER (pers. comm. 1982). The highest uranium contents (up to 74 ppm) can be found in the apatites of the Granatspitz gneiss massif in the center of the Tauern Window. The apatites of some small augengneiss bodies belonging to the Keller Joch and the Steinkogel units north of the Tauern Window in the Austroalpine area show rather high uranium contents of around 50 ppm.

The uranium, thorium and potassium contents of 27 selected whole rock samples have been determined by INAA in order to estimate the heat production in the lithologies studied due to the radioactive decay of the U, Th and K isotopes (Tab. 2).

The heat production was calculated from the U, Th and K contents according to the formula given by RYBACH (1976) (Tab. 2). From this table and by comparison with Fig. 7 it can be seen that there is no correlation between the U content of the apatites and that of the rocks or between the U content of the apatites and the overall heat production.

Most of the rocks are augen- and flasergneisses showing textures and chemical compositions consistent with a magmatic protolith. The question arises whether the lack of correlation between the U-content of the apatites and the rocks is a primary magmatic feature or was achieved by the apatites during metamorphism.

In Fig. 8 the U-distribution for an apatite from the Granatspitz area is shown. From the fission track density it is obvious that the apatite displays a zonal distribution of the uranium. A compositional zoning due to changing conditions of metamorphism is common in most of the minerals from the Penninic rocks of the Tauern Window (see MORTEANI, 1971; MORTEANI & RAASE, 1974). A redistribution of the uranium inside the rocks during the metamorphism seems to be very probable, but the reason why the metamorphic apatites in the gneisses of the Granatspitz show a very preferential uptake of uranium remains unknown.

Table 2: Comparison of the heat production as derived from U, Th and K content of 27 selected whole rock samples; additionally the U content of apatite separated from the whole rock samples.

No.	sample	whole rock density	apatite U [ppm]	rock U [ppm]	rock Th [ppm]	rock K [%]	A (HGU)*
1	SP 79.01	2.70	6.4	2.8	17	1.9	4.98
2	SP 79.05	2.67	26	4.4	3.6	3.3	4.00
3	SP 79.06	2.67	32	3.8	13	4.3	5.53
4	SP 79.07	2.67	47	6.8	12	4.0	7.01
5	SP 79.14	2.67	13	2.8	13	2.1	4.31
6	SP 79.27	2.67	22	1.5	5.1	7.2	3.36
7	SP 79.28	2.70	12	2.6	12	2.5	4.17
8	SP 79.31	2.70	49	3.4	22	4.5	6.77
9	SP 79.41	2.67	8.3	1.9	14	3.1	4.14
10	SP 79.43	2.70	5.7	2.3	4.0	1.8	2.49
11	SP 79.45	2.70	12	3.8	11	3.7	5.01
12	SP 79.49	2.72	10	< 1.5	15	2.3	3.87
13	SP 79.52	2.72	11	3.4	7.5	2.4	3.89
14	SP 79.53	2.67	11	2.9	17	4.1	5.47
15	SP 79.54	2.72	11	2.1	8.3	2.8	3.30
16	SP 79.57	2.70	20	3.3	12	3.7	4.87
17	SP 79.60	2.67	2.6	4.8	4.7	2.4	4.24
18	SP 79.61	2.70	74	1.9	14	2.8	4.12
19	SP 80.66	2.70	40	4.5	6.8	4.1	4.83
20	SP 80.67	2.80	2.1	4.0	13	2.2	5.30
21	SP 80.69	2.80	1.3	6.7	4.6	2.8	5.72
22	SP 81.87	2.67	14	42	21	4.0	30.01
23	SP 81.89	2.67	43	5.5	12	3.7	6.15
24	SP 81.91	2.67	14	7.5	28	3.4	9.93
25	SP 81.92	2.67	41	6.0	9.1	3.5	5.94
26	SP 81.99	2.67	5.2	4.1	15	3.2	5.67
27	SP 81.100	2.67	4.6	7.9	26	3.0	9.76

*) A (HGU) calculated after RYBACH (1976)
$A\ (HGU) = 0.317\ \varrho\ (0.718 C_U + 0.193 C_{Th} + 0.262 C_K)$
$1\ (HGU) = 10^{-13}\ cal/cm^3 sec$

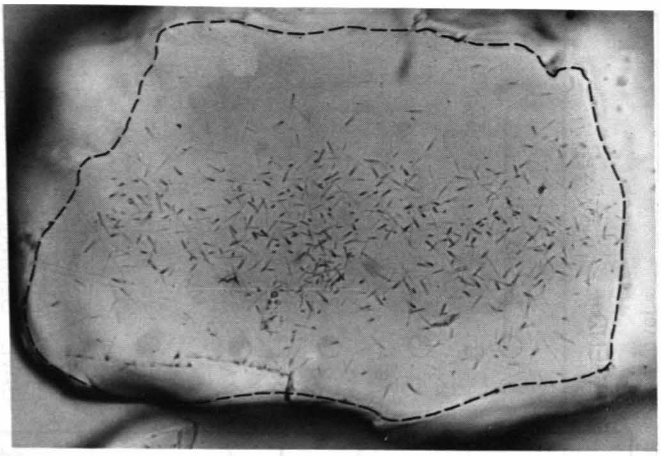

Fig. 8: Inhomogeneous distribution of fission tracks in an apatite separated from the "Augen- und Flasergneise" of the Granatspitz massif, central Tauern Window.

Evidence of mobilization of U (and Pb) during Alpine metamorphism was obtained also by CLIFF & COHEN (1980) from uranium-lead isotope studies on the Penninic metatonalites in the eastern Tauern Window.

Both the Rb/Sr and K/Ar ages are influenced by the elevation of the samples. Unfortunately the elevation of the sampling point for many of the published Rb/Sr and K/Ar mica cooling age determinations is not given in the papers. For the comparison of the Rb/Sr and K/Ar cooling ages with the apatite fission track ages a reference level of 1800 m above sea level was chosen. The elevation of 1800 m above sea level was chosen due to the fact that most reliable Rb/Sr and K/Ar mica cooling ages have been determined only on rock samples collected at this elevation.

In Fig. 9 apatite fission track ages as well as cooling ages of biotite and white mica are plotted versus the closure temperature of the fission tracks in apatite and the closing temperature of the Rb/Sr- and K/Ar-system.

From the Habachtal to the Krimmler Achental, the Zillergrund and the Schlegeistal, i. e. from the central to the western Tauern Window, the fission track ages as well as the mica cooling ages become increasingly younger. In Fig. 9 the fission track ages of the Kellerjoch, the Arntal and the Granatspitz area are also plotted for comparison. Unfortunately no mica cooling ages are known from the Kellerjoch and the Granatspitz areas.

The uplift and the cooling history of a given area is influenced by the density distribution of the column of rocks beneath the area. The regional density distribution in the area studied is shown in Fig. 10 by the isogals of the Bouguer anomaly according to MAKRIS (1971). A comparison of Fig. 4 with Fig. 10 shows that young fission track ages are found in the area characterised by a strong negative Bouguer anomaly. The very young ages are found in the Granatspitz gneiss-massif, within an area in which the most negative Bouguer anomaly (– 170 mgal) of the Eastern Alps occurs.

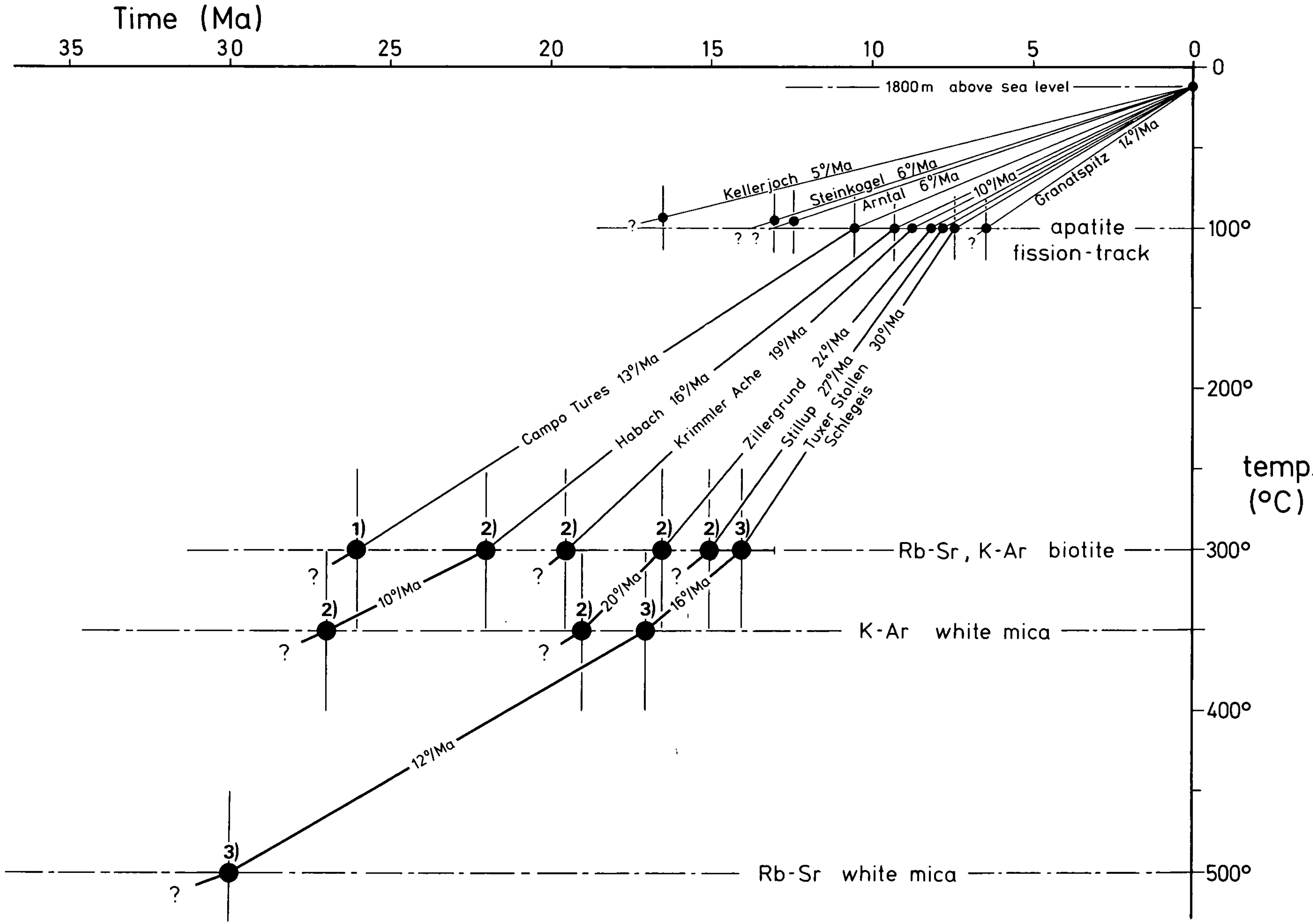

Fig. 9: Cooling history of selected areas within the central and western Tauern Window as deduced from different age determination methods. All values are referred to the reference level of 1800 m above sea level.
[1]HAMMERSCHMIDT (1981); [2]RAITH et al. (1978); [3]SATIR (1975).

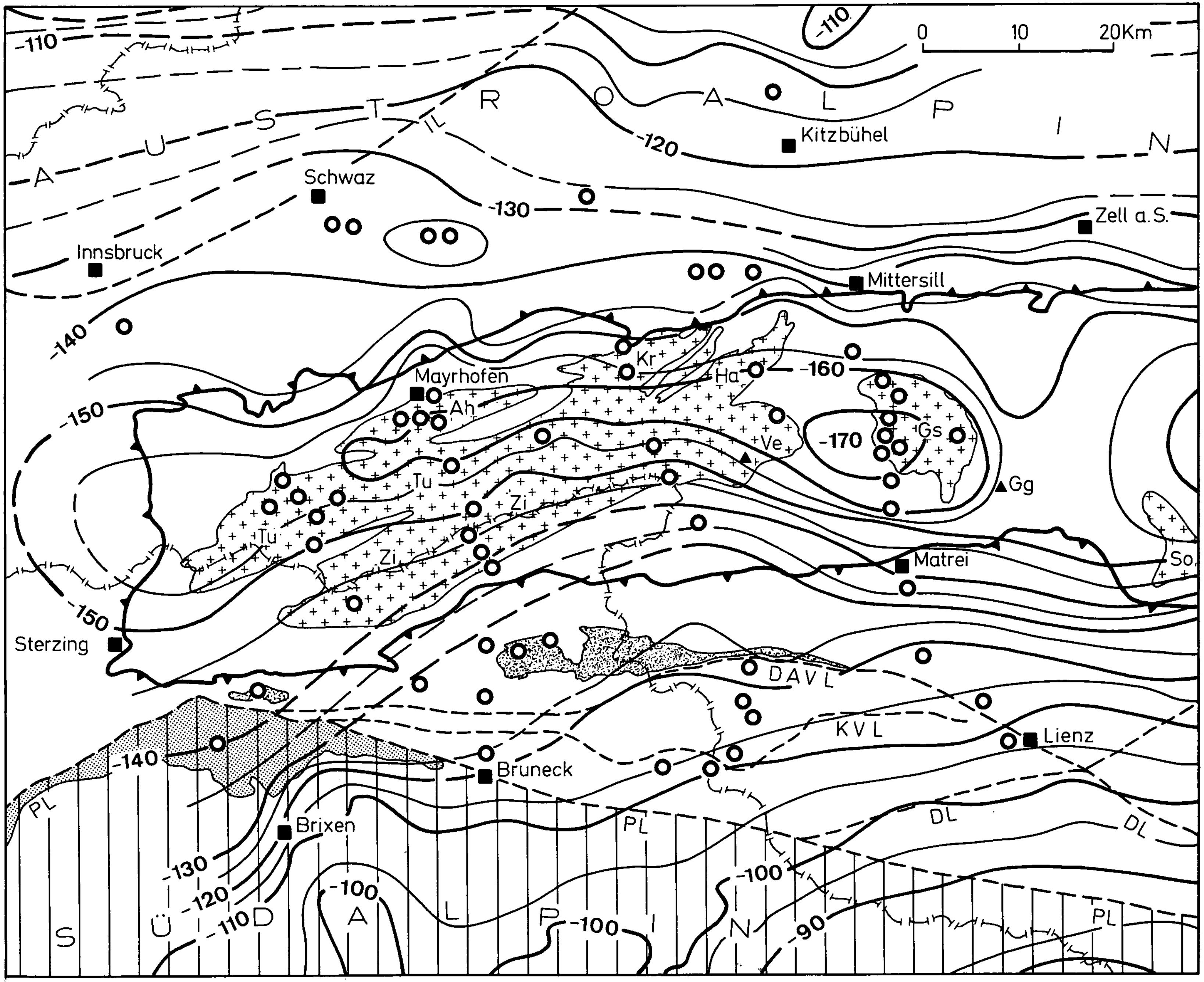

Fig. 10: Sampling points (open dots) and isogals of the Bouguer anomalies in the investigated area according to MAKRIS (1971).

4. Discussion

A depth of about 2000 m below sea level is suggested for the 100°C isotherm by the extrapolation of the regression lines representing the uplift rates for the areas of the Habachtal, Krimmler Achental, Stilluptal and the Schlegeistal (Fig. 5). All these areas are situated in the central axis of the Eastern Alps in the Penninic domain; this is known to be the deepest tectonic unit of the Eastern Alpine pile of nappes. A depth of 2000 m for the 100°C isotherm corresponds fairly well to the depth of the current 120° isotherm as given by WAGNER et al. (1977) for the Central Alps in Switzerland.

For the areas of the Arntal, the Steinkogel and the Kellerjoch a depth of only 1000 m below sea level is suggested for the 100°C isotherm (Fig. 5). The Arntal is situated to the south, and the Kellerjoch and the Steinkogel to the north of the Tauern Window within the Austroalpine domain. The depth of the 100°C isotherm for these areas results in a calculated geothermal gradient of 37°C/km which is 7°C/km higher than that resulting in the Penninic areas. A much lower geothermal gradient of not more than 22°C/km is given for the Austroalpine Area north of the Tauern Window by HUFNAGEL et al. (1981).

Unfortunately no detailed geothermal data exist for the study area. From the few data given by HAENEL (1976) on the heat flow in the Eastern Alps, the heat flow in the area of the Tauern Window seems to be markedly lower than in the Austroalpine domain north and south of the Tauern Window. A reduced heat flow for the Austroalpine domain sometime between the Late Cretaceous and the present was demonstrated by TEICHMÜLLER et al. (1978).

The high position of the isotherm as constructed by linear extrapolation in Fig. 5 for the Austroalpine domain is consistent with the recent high thermal flux in this area as observed by HAENEL (1976). From this consistency and the convergence of the extrapolations at a depth of 2000 m below sea level, the linear approximation of the uplift rate may be justified. It is obvious from general considerations that a non linear function for the time dependent uplift rates must be assumed.

In comparison with the Central Alps (WAGNER et al., 1977) the different areas studied in this work show, with the exception of the Granatspitz gneiss massif, a rather continuous development of the uplift rate for the time span covered.

K/Ar mica ages according to RAITH et al. (1978), Rb/Sr mica ages according to SATIR (1975) and JÄGER (1969) and apatite fission track ages (present work) from the Tauern Window are plotted in Fig. 11 in a WSW to ENE profile starting from the Brenner pass and ending in the Felbertal/Granatspitz area. From WSW to ENE an increase of the cooling ages as referred to the same elevation can be observed. This indicates that in the western part of the Tauern Window the rocks were cooled down below 100°C later than in the central part, in accord with the fact that the uplift rate was higher in the western part.

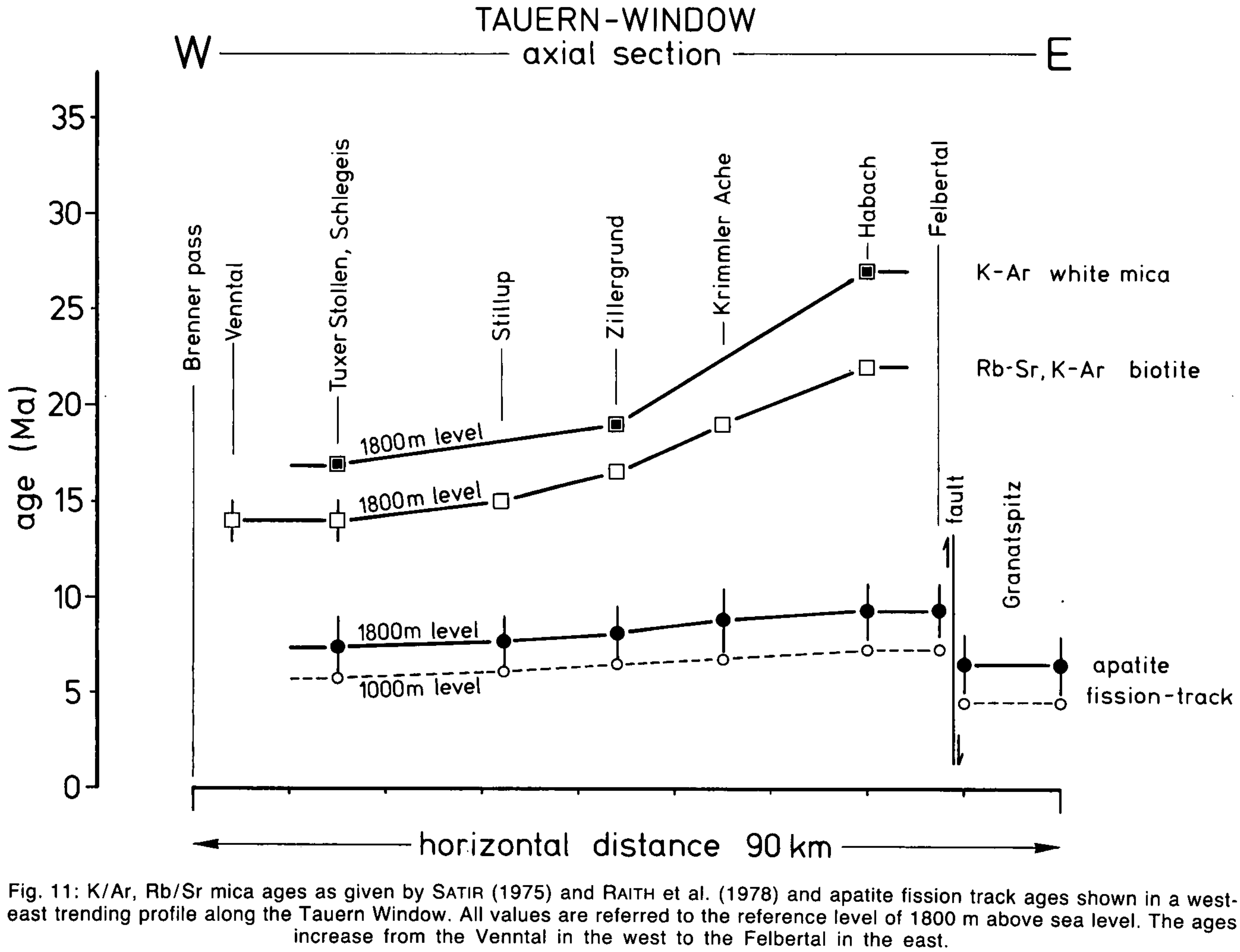

Fig. 11: K/Ar, Rb/Sr mica ages as given by SATIR (1975) and RAITH et al. (1978) and apatite fission track ages shown in a west-east trending profile along the Tauern Window. All values are referred to the reference level of 1800 m above sea level. The ages increase from the Venntal in the west to the Felbertal in the east.

The difference between the uplift rates of the eastern and the western part of the study area can be visualized in a tentative reconstruction of the depth related cooling ages (Fig. 12) using the same WSW to ENE trending profile as represented in Fig. 12. The mica cooling ages and the apatite fission track ages resp. are taken from Fig. 9, so that they are referred to an elevation of 1800 m above sea level. The depths at which the closing temperatures of 100°, 300° and 350°C are supposed are calculated from a constant geothermal gradient of 30°C/km. Such a gradient was suggested by WAGNER et al. (1977) for the Central Alps and by SASSI et al. (1974) for the Eastern Alps. Cooling isochrons obtained by interpolation of the measured ages are given in open dots and show about identical depth intervals in the eastern part of the profile i. e. Krimmler Ache and Habachtal. This indicates at least for the Habachtal area a rather constant uplift rate during the last 20 Ma, whereas changing intervals in the western part of the profile show from 10 Ma downwards the strongly decreasing uplift rates of the western Tauern Window.

A particular problem is posed by the Granatspitz area. The Granatspitz gneiss massif is situated in the central Tauern Window. From the results obtained from the other areas within the Tauern Window a depth of about 2000 m below sea level should also be supposed for the 100°C isotherm in the Granatspitz area. An extrapolation of the fission track ages, however, shows a very shallow depth for the 100°C isotherm at about 1000 m below sea level. This depth is similar to that calculated for the Austroalpine domain. The uplift rate for the time span covered by the fission track ages (5 to 9 Ma) is very similar to those found in the other areas inside the Tauern Window, particularly to those of the Habachtal and the Krimmler Achental. Furthermore, the youngest fission track ages of the whole study area have been determined in the area of the Granatspitz. For an explanation of the fission track cooling ages at least three models have to be discussed:

❶ In the time span between the youngest fission track age and the present, the Granatspitz experienced due to faulting a faster uplift rate than the surroundings (especially of the western part of the Granatspitz). In such a case the linear extrapolation of the age versus elevation function to the present time would be wrong. If at the present a depth of 2000 m below sea level is supposed for the 100°C isotherm, the uplift rate of the tectonically isolated Granatspitz gneiss massif increased in the time span 5 Ma to the present time from originally 0.4 mm/a to 0.6 mm/a (see Fig. 5).

❷ The isotherms in the area of the Granatspitz are closer together than in the surroundings due to an anomalously high heat production inside the granitic rocks forming the Granatspitz gneiss core. At first glance, an anomalously high heat production may be deduced by the relatively high uranium content of the apatites. However the determination of the most important heat producing elements (U, Th, K) in se-

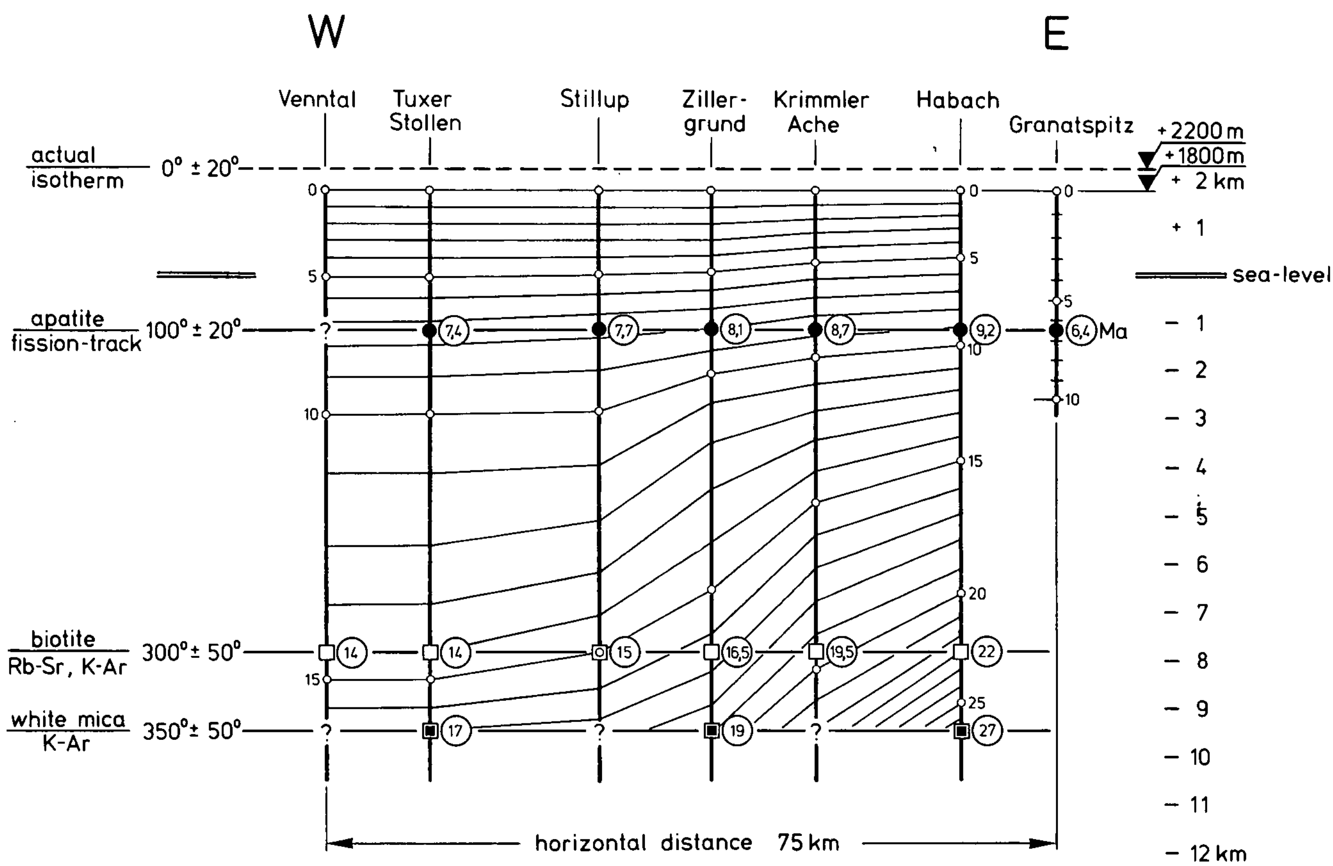

Fig. 12: K/Ar white mica, K/Ar and Rb/Sr biotite ages as given by SATIR (1975) and RAITH et al (1978) and apatite fission track ages given in this paper and closure temperatures in a west-east trending cross section from the Venntal to the Granatspitz. The position of the profile is the same as in Fig. 11. The figures near the vertical lines are the ages measured (given in solid symbols) or interpolated (open symbols). The subhorizontal lines are cooling isochrons. The geothermal gradient in the whole area is assumed to be constant at 30°C·km^{-1}. From the variation of the distances between the cooling isochrons it can be seen that the uplift rate in the east was more constant than in the west (Further details see text).

lected whole rock samples does not show a particularly high concentration of these elements, and consequently does not indicate an anomalously high heat production in the Granatspitz.

❸ The Granatspitz massif was affected by high heat flow due to an unknown underlying heat source but no data exist concerning the amount of heat production supplied by deeper crustal levels in this area.

From the data available the most probable explanation of the age anomaly found in the Granatspitz seems to be No. ❶ mainly from the fact that subvertical faults can be found at the western border of the Granatspitz gneiss massif, suggesting important vertical movements (PESTAL, 1983; HÖLL, 1975). Furthermore the dome-like structure of the Granatspitz gneiss massif may suggest an isolated updoming due to slip along the schistosity. No definite proof for such a mechanism can be found, but it must be taken into account that movements subparallel to the main schistosity are difficult to recognize and their importance is therefore hard to assess.

The most serious problem is represented by the fact that the postmetamorphic cooling history reported by the fission track ages could have been not only related to the regional heating of the Tauernkristallisation with a maximum at around 40 Ma (see e. g. RAITH et al., 1978) but wholly or partially to a younger regional heating event, called by some authors "third alpine metamorphism" or "Neo-Alpine event" at around 20 Ma (see e. g. BORSI et al., 1973; SASSI et al., 1974, 1980). Both views are discussed in KREUZER et al. (1978). Plotting our fission track ages as well as the Rb/Sr and K/Ar mica cooling ages from SATIR (1975) and RAITH et al. (1978) it can be seen that even for the extreme cases Schlegeis in the west and Habach in the east of the study area (Fig. 13) the hypothesis of a late Alpine metamorphic event at 20 Ma due to a heat dome seems to be unrealistic. A very local heat dome between the areas of Habach and Schlegeis is prohibited by the continuous change of the fission track ages and the Rb/Sr and K/Ar mica cooling ages along the profile from Schlegeis to the Habach area (Fig. 11 and Fig. 12).

The sample No. SP 80.67 collected near Kitzbühel in the Austroalpine Grauwackenzone in the extreme north of the studied area gives an age of about 42 Ma. An age of about 22 Ma is given by the sample No. Sp 81.86 situated in the same tectonic unit about 20 km SW of sample SP 80.67. These two ages fall roughly in the time span of the maximum temperature of the middle Alpine Tauernkristallisation. It seems therefore likely that these apatite fission track ages represent original cooling ages of the Eoalpine late Cretaceous metamorphism or mixed Eoalpine and middle Alpine ages. The maximum temperature of the Eoalpine event was estimated by SATIR & MORTEANI (1979) from K/Ar data on micas to be below 300°C in the Austroalpine Steinkogel area south of Kitzbühel.

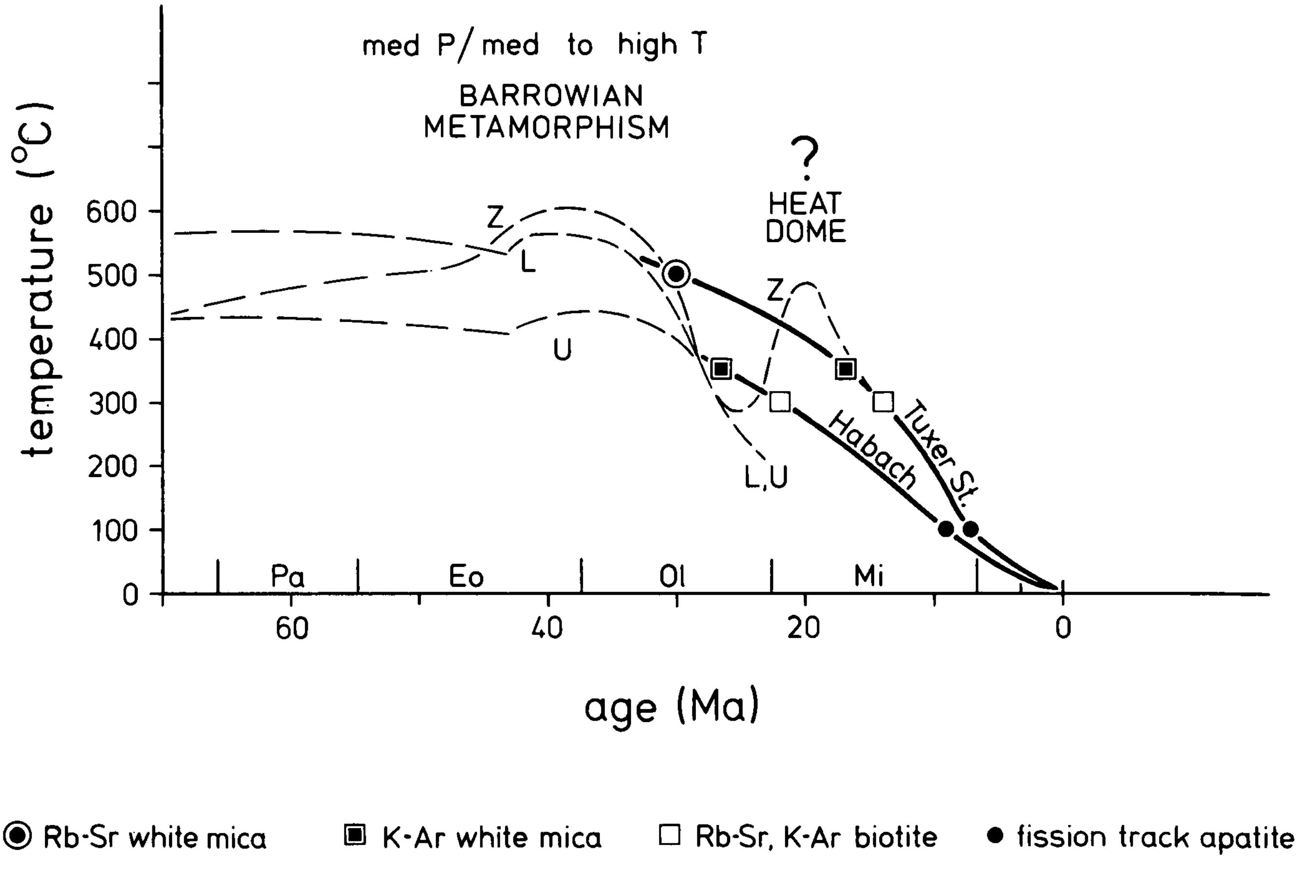

Fig. 13: Temperature versus age diagramm for the Zentralgneis (Z), the Upper Schieferhülle (U) and the Lower Schieferhülle (L) with a temperature/time path as given by KREUZER et al. (1978) (dashed lines). The Rb/Sr and the K/Ar mica ages from JÄGER et al. (1969), SATIR (1975) and RAITH et al. (1978) as well as the apatite fission track ages given in this paper (solid lines) invalidate the evidence of a "heat dome" or "third Alpine event" at 20 ma. Further explanations see text.

5. Conclusions

Comparing our results with those of WAGNER et al. (1977) from the Central Alps it is evident

a) that the uplift pattern of the investigated area is more homogeneous than that of the Central Alps and
b) that the uplift rates of the central part of the Eastern Alps remained rather constant from 20 Ma to the present time whereas for the Central Alps a change in the uplift rate in all areas at various times has been observed.

A discrepancy exists between our data and the uplift rates as determined by SENFTL & EXNER (1973) on the basis of repeated levelling measurements. They give a recent uplift rate of around 1 mm/a for the profile following the railroad track from Mallnitz to Badgastein in the eastern Tauern Window. A similar uplift rate of 0.7 mm/a was calculated by MORTEANI (1974) from Rb/Sr and K/Ar age determinations taken from JÄGER et al. (1969). Uplift rates of 0.4 mm/a identical to those given in this paper have been deduced from geological considerations by RAITH et al. (1980) for the southern Venediger area. FRISCH (1976) assumed 0.5mm/a for the central axis of the western Tauern Window, an uplift rate identical to that given in this paper.

The extrapolation of the recent position of the 100°C isotherm below and outside the Tauern Window as shown in Fig. 5 supports the heat flow determinations of HAENEL (1976) showing a lower heat flow inside the Tauern Window than in the Austroalpine domains.

Comparison of the fission track ages with the K/Ar and Rb/Sr mica ages measured across the DAV- and the KV-tectonic lines suggests that the last movements with significant vertical displacement occurred along these lines before 20 Ma.

A revision of the temperature versus time diagram as given by KREUZER et al. (1978) for Upper Cretaceous to recent times shows that there is no evidence for a third Alpine metamorphism in the Penninic units of the central and western Tauern Window at around 20 Ma (Fig. 13).

The evaluation of our fission track data and of the Rb/Sr and K/Ar data of other authors show that the discussion of the cooling history of an area with strong topography like that studied has to be based on age data carefully referred to the same elevation.

Some rather old fission track ages (42 and 22 Ma) in the Austroalpine area near Kitzbühel are probably original cooling ages of the Eoalpine event rather than of the middle Alpine Tauernkristallisation. From this it may be concluded that the anchimetamorphism demonstrated e. g. by SCHRAMM (1978, 1980) in the Austroalpine Calcareous Alps occurred before their overthrusting over the Penninic tectonic unit.

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