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Apatite Fission-Track Evidence for Postmetamorphic Uplift and Cooling History of the Eastern Tauern Window and the Surrounding Austroalpine (Central Eastern Alps, Austria)

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With 10 Figures and 1 Table

Ostalpen
Austroalpin
Penninikum
Tauernfenster
Tauernkristallisation
Radiometrische Altersbestimmungen
Apatit-Spaltspuren-Alter
Hebungsraten
Abkühlungsgeschichte

Contents

Zusammenfassung

Mit Hilfe von 62 Apatit-Spaltspurendatierungen wurde die nach dem Abklingen der spätalpinen Regionalmetamorphose (Tauernkristallisation) fortschreitende Hebung und Abkühlung des östlichen Tauernfensters und seiner ostalpinen Umrahmung untersucht. Die Bestimmung der Apatit-Spaltspurenalter erfolgte nach der Populationsmethode.

Die Apatit-Spaltspurenalter sind Abkühlungsalter mit einer Schließungstemperatur von ca. 100°C. Die Standardabweichung der Alter beträgt ±10 %.

Innerhalb des Tauernfensters und im Randbereich des ostalpinen Altkristallins (Polinik Gebiet) liegen die Apatit-Spaltspurenalter zwischen 6 und 23.4 Ma. Im Bereich des Kreuzecks (Altkristallin) steigen die Alter bis zu 31.4 Ma. Die älteste Probe mit 57.6 Ma stammt aus der ostalpinen Grauwackenzone bei Saalfelden. Dabei handelt es sich wahrscheinlich nicht mehr um ein Abkühlungsalter der alpinen Tauernkristallisation (Temperaturmaximum zwischen 185–92 Ma), sondern eher um ein Mischalter oder Abkühlungsalter einer frühalpinen Metamorphose (Temperaturmaximum ziwschen 90 und 80 Ma).

Für ausgewählte Gebiete wurden über angenähert vertikale Probenprofile folgende Hebungsgeschwindigkeiten bestimmt: Sonnblick/Siglitz 0.24 mm/a; Großglockner 0.2 mm/a; Reißeck/Polinik 0.16 mm/a und Kreuzeck 0.1 mm/a. Diese Werte gelten für den Zeitraum zwischen 6 und 31 Ma.

Zusammen mit den Ergebnissen von GRUNDMANN & MORTEANI (1985) ergibt sich, daß innerhalb des Tauernfensters die Apatit-Spaltspurenalter kontinuierlich von West nach Ost zunehmen und die Hebungsgeschwindigkeiten abnehmen. Das ostalpine Altkristallin des Polinik-Gebietes unterlag einer gleichen Hebungs- und Abkühlungsgeschichte wie das benachbarte Penninikum des Reißecks.

Die Abkühlungsgeschwindigkeiten der Gesteinsserien des Tauernpenninikums und des ostalpinen Alkristallins liegen im Niedertemperaturbereich (von 100°C bis zur heutigen Oberflächentemperatur) zwischen ca. 4 und 9°C/Ma.

Mit Ausnahme einer Altersanomalie im Bereich von Badgastein, die nur hypothetisch erklärt werden kann, verlief die Hebung und Abkühlung des Tauernfensters für den datierten Zeitraum insgesamt sehr homogen.

Summary

Apatite fission track ages of 62 samples from within the eastern Tauern Window and from its borders were determined by the population method, the ages interpreted as cooling ages following the alpine metamorphism (Tauernkristallisation), assuming a closure temperature of 100°C. They are accurate to ±10 %.

Fission track ages from within the Tauern Window and from the Austroalpine Altkristallin units (Polinik area) are between 6 and 23.4 Ma. In the Kreuzeck area (Altkristallin) the ages increase to 31.4 Ma. The oldest sample, dated 57.6 Ma, comes from the Grauwackenzone near Saalfelden. This age is probably a aooling age from the early alpine metamorphism (peak at 185–92 Ma) rather than the Tauernkristallisation (peak at 30–50 Ma).

Vertical sampling profiles in selected areas gave the following uplift rates: Sonnblick/Siglitz 0.24 mm/a; Großglockner 0.2 mm/a; Reißeck/Polinik 0.16 mm/a and Kreuzeck 0.1 mm/a. These rates are valid for the period between 6 and 31 Ma.

The results of this study combined with those from GRUNDMANN & MORTEANI (1985) in the western Tauern Window show that the apatite fission track ages increase continuously from west to east within the Tauern Window, and the uplift rates continuously decrease. The Austroalpine Altkristallin in the Polinik area underwent the same uplift and cooling history as the adjacent Penninikum of the Reißeck area.

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The rocks of the Tauern Penninikum and the Austroalpine Altkristallin have cooled from the apatite closing temperature (100°C) to the present surface temperature at between 4 and 9°C/Ma.
With the single exception of the Badgastein area, which can be hypothetically explained, the uplift and cooling of the Tauern Window for the dated period was very homogenous.

1. Introduction and Problem

Based on a study of 62 fission track ages from apatite, the main intention of this paper is to analyse the young uplift and thermal history of the Penninic rocks of the eastern Tauern Window and the surrounding Austroalpine (= Eastalpine) rocks. The investigated area is shown in fig. 1 on a geological sketch map of the eastern Alps. The fission track ages of apatite are cooling ages (WAGNER, 1968; WAGNER & REIMER, 1972). In the western Tauern Window GRUNDMANN & MORTEANI (1985) calculated cooling rates between 13°C/Ma and 30°C/Ma combining apatite fission track ages with K/Ar and Rb/Sr ages in biotite. Similar high cooling rates should also be expected for the eastern Tauern Window (CLIFF & OXBURGH, 1971).

As in the Central Alps (WAGNER & REIMER, 1972; WAGNER et al., 1977) an increase of the apatite fission track ages with increasing topographic elevation was observed in the western Tauern Window by GRUNDMANN & MORTEANI (1985), indicating uplift rates between 0.2 und 0.5 mm/a.

In the eastern Tauern Window Rb/Sr and K/Ar radiometric cooling ages of biotite and white mica in the Penninic and Austroalpine rocks are reported by OXBURGH et al. (1966), LAMBERT (1970), HAWKESWORTH (1976), WATERS (1976), BRACK (1977) and PEER & ZIMMER (1980). The closure temperature of Rb/Sr and K/Ar in biotite is about 300°C±50°C, for K/Ar in white mica 350°C and 500°C for Rb/Sr in white mica (PURDY & JÄGER, 1976; JÄGER, 1979). These closure temperatures are 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 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.

OXBURGH et al. (1966) noted an abrupt break in the pattern of the K/Ar ages at the "Mölltal" line at the edge of the southeast Tauern Window. Inside the window most ages are about 20 Ma. In the Austroalpine "Altkristallin" units outside the window both the Rb/Sr and K/Ar cooling ages are about 80 Ma. These ages reflect the last thermal events in and outside the eastern Tauern Window, respectively.

The most important thermal event in the Penninic rocks of the Tauern Window was the mid-Tertiary "middle Alpine" (VAN EYSINGER, 1975) regional metamorphism, also called "Tauernkristallisation" (SANDER, 1911, 1921), "late Alpine" (DROOP, 1985), "Mesoalpine" (KREUZER et al., 1978) or "main Alpidic event" (RAITH et al., 1978). This Barrovian metamorphism reached its

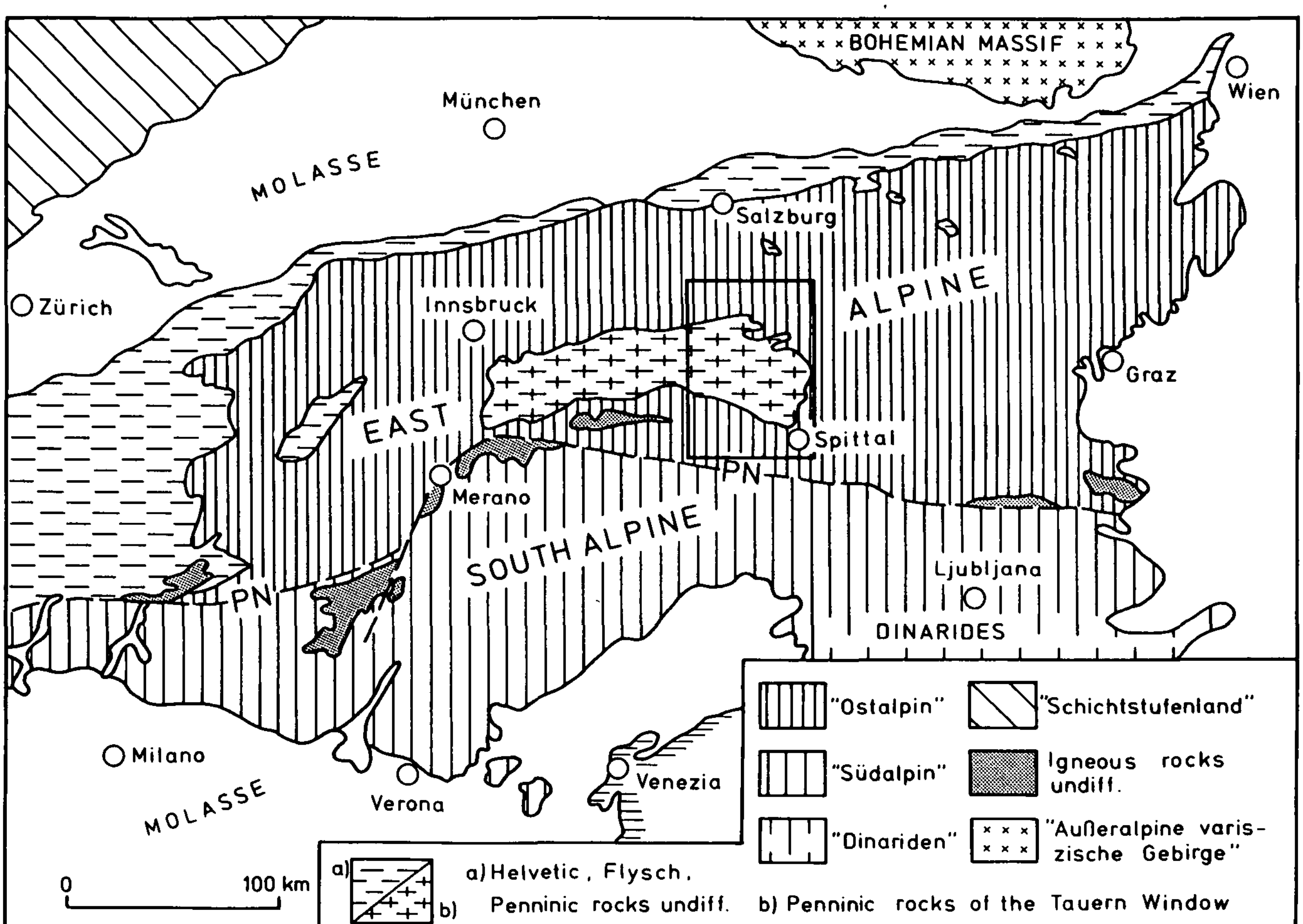

Fig. 1.
Geological sketch map of the Eastern Alps with investigated area.

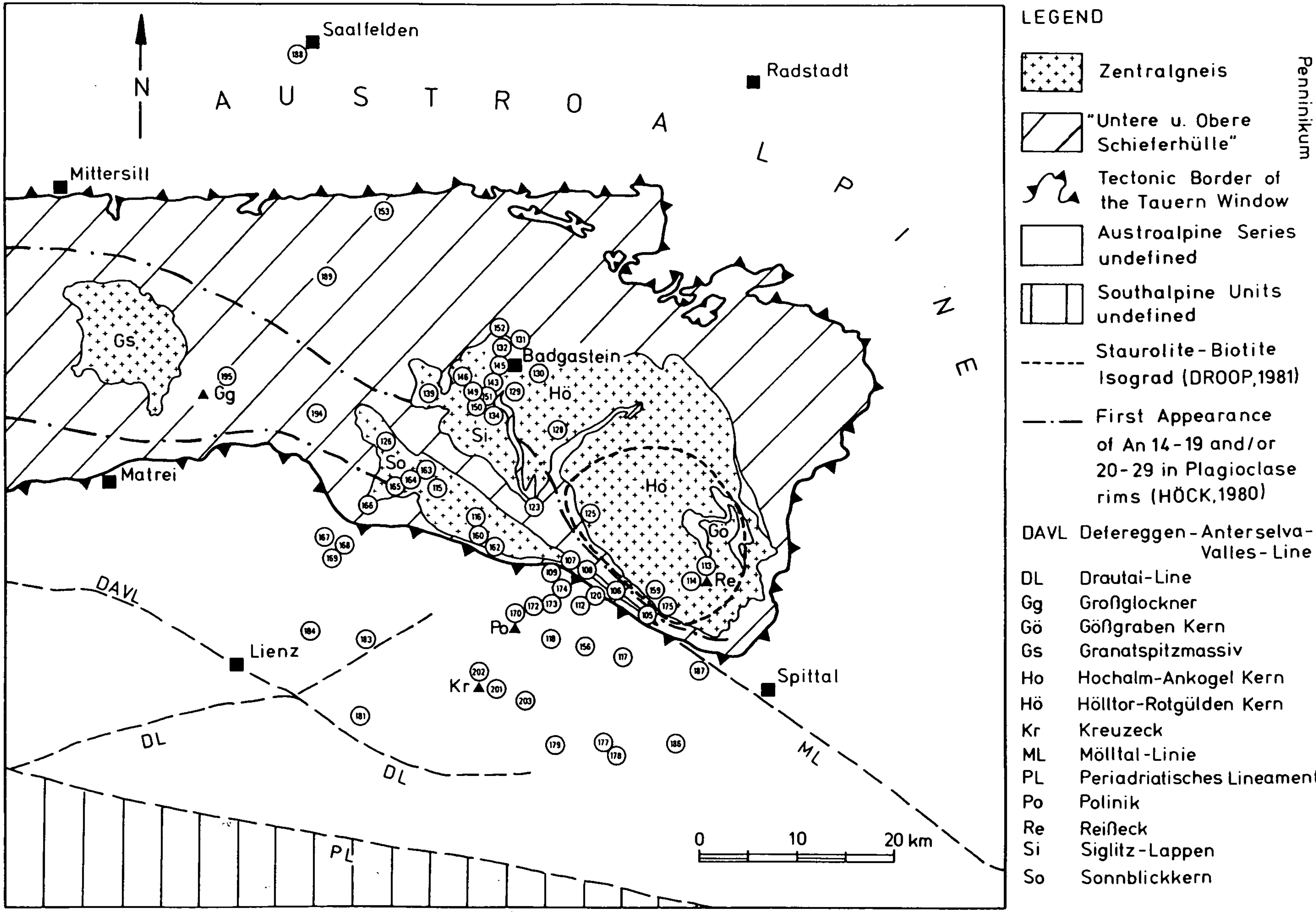

Fig. 2.
Sampling localities and isograds of the Alpine regional metamorphism ("Tauernkristallisation") in a simplified geological sketch map.

peak between 65 Ma and 30 Ma. For the Penninic rocks of the western Tauern Window a younger metamorphism than the middle Alpine Tauernkristallisation at 20 Ma was suggested by BORSI et al. (1973), SASSI et al. (1974, 1980) and RAITH et al. (1978). Based on apatite fission track ages GRUNDMANN & MORTEANI (1985) could show that there is no evidence for the existence of this 20 Ma old low grade „Neo" or "third Alpine" metamorphism in the Penninic rocks of the western and central Tauern Window. The possibility of such a late thermal event has never been discussed for the eastern Tauern Window.

The general characteristics of the Tauernkristallisation in the Penninic rocks of the study area are known e. g. from the studies of EXNER & FAUPL (1970), CLIFF et al. (1971), DROOP (1979, 1981, 1982, 1985), PEER & ZIMMER (1980) and HÖCK & HOSCHECK (1980). The published isograds are given in fig. 2 according to HÖCK (1980) and DROOP (1981). They are roughly parallel to the border of the Tauern Window.

The last regional metamorphic event in the Austroalpine units farther outside the border of the Tauern Window was the Early Alpine or Eoalpine event according to KREUZER et al., 1978). Radiometric age determinations in the polymetamorphic Austroalpine units south of the eastern Tauern Window (see above) and to the north (KRALIK, 1983) dated this metamorphic event at before 90 Ma. The metamorphic conditions in the Austroalpine units north and south of the eastern Tauern Window are given e. g. by SCHRAMM (1980), COLINS et al. (1980) and WATERS (1976).

2. Sampling and Experimental Methods

Fig. 2 shows the sampling localities in a simplified geological sketch map. The area sampled is limited roughly by the towns of Saalfelden and Radstadt in the north and Lienz and Spittal in the south. The area covered is about 5000 square km. The elevations of the sampling localities are between 570 m and 2963 m above sea level. From a total of 99 rock samples collected 37 turned out to be unsuitable, being too poor in apatite or containing apatites with very low uranium content (<1 ppm). 38 samples from within the eastern Tauern Window, 23 from the southern Austroalpine „Altkristallin" and 1 from the northern Austroalpine Grauwackenzone were suitable for dating. The sample weight varied in all cases between 3 and 5 kg. (a list of the studied samples including petrographic descriptions and details of the sampling localities is available from the author on request).

For fission track dating nearly pure apatite concentrates of some 100 to several 1000 apatite grains were separated from the rock samples (primarily granitic gneisses and also from metabasic rocks and calc-mica-schists). The apatites were dated with the population technique (WAGNER, 1968; HAACK, 1975; NAESER, 1976). The experimental conditions are given in detail by GRUNDMANN & MORTEANI (1985). The irradiation of the annealed samples was carried out in the thermal column of the reactor BER II at the Hahn-Meitner-Institut für Kernforschung in Berlin-West. The neutron flux density inside the thermal column was about 10^{10} n/cm^2·s. The ratio of epithermal to total thermal neutrons was 1 %. The neutron dose was determined with Al-wires containing 1.000 %, 0.501 % and 0.528 % Co as monitor. The activity of the Co-content was measured with a "Harshaw Ge (Li)" detector and a "Canberra 8622" multichannel analyser according to the method of BRINKMANN et al. (1963) and SCHLEY (1977). From the activity the neutron dose was calculated after DE SOETE et al. (1972). The dose values were checked with the dosimeter glass "Trebic" (moldavite standard, obtained from WAGNER, MPI Heidelberg). The irradiated and unirradiated samples were etched together in 5 % HNO_3 for 45 s at 21°C.

3. Results

In table 1 the track counting data, their statistical errors and the resulting ages are presented according to the suggestion of NAESER et al. (1979).

The following formula was used for the calculation of the fission track ages:

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

where:

ps = number of spontaneous fission tracks per cm^2
pi = number of induced fission tracks per cm^2
I = ratio of isotopes $^{235}U/^{238}U = 7.27 \times 10^{-3}$ (ROGERS & ADAMS, 1972)
σ = D = number of thermal neutrons per cm^2
λ_f = decay constant = $8.46 \times 10^{-17} a^{-1}$ (GALLIKER et al., 1970)
T = fission track age in million years

The uranium contents in column (11) range from <1 ppm up to 30 ppm in the apatite samples. This variation just reflects the different host rock types.

The apatite fission track ages are cooling ages. The closure temperature is dependent on the cooling rate of the apatite-bearing rock (NAESER & FAUL, 1969; DODSON, 1979). Using the cooling rates between 13°C/Ma and 30°C/Ma, which were calculated by GRUNDMANN & MORTEANI (1985) for the western Tauern Window also for this study the closure temperature is 100°C according to DODSON (1979). This closure temperature is used for the further interpretation of the apatite fission track ages.

The regional distribution of the measured fission track ages is given in fig. 3. Inside the eastern Tauern Window the ages range from 6 Ma to 23.4 Ma. In the Austroalpine "Altkristallin" (Polinik area) near the border of the Tauern Window the ages are similar. In the southern "Altkristallin" (Kreuzeck area) more distant from the border of the Tauern Window the apatite fission track ages reach values up to 31.4 Ma. The oldest measured sample with 57.6 Ma comes from the "Grauwackenzone" (Saalfelden) north of the Tauern Window.

For determination of the uplift rates samples were collected from more or less vertical profiles. A comparison of the fission track ages with the topographic elevation of the samples shows that some of the areas have nearly identical ages at the same topographic level – thus these areas had the same uplift history. The individual profiles can thus be considered in three groups: Sonnblick/Siglitz incl. Großglockner, Reißeck/Polinik and Kreuzeck. In figs. 4 and 5 the elevation of the sampling points (meters above sea level) is plotted against the corresponding fission track ages. The uplift rate of each group is given by the slope of the least squares regression line (heavy line). The numbers near the lines

Table 1.
Fission track data table.

(1)	(2)	(3)		(4)		(5)	(6)	(7)*	(8)	(9)	(10)		(11)**
sample code	elev. above sea level	ps		pi		D $\times 10^{14}$ neutr. /cm²	T age (ma)	±σ	number of grains or fields	field size mm²	S_s relative error of mean %	S_i	U ppm
		tracks /cm² $\times 10^5$	tracks	tracks /cm² $\times 10^5$	tracks								
1. SP 81.105	720m	0.70	212	1.40	424	3.537	8.8	0.8	300/300	0.001	5.1	6.9	14.4
2. SP 81.106	900m	0.64	129	1.17	235	3.781	10.3	1.2	200/200	0.001	7.0	9.7	11.3
3. SP 81.107	820m	0.64	191	1.30	390	3.626	8.8	0.8	300/300	0.001	5.4	7.5	13.1
4. SP 81.108	790m	0.52	135	1.18	236	3.453	9.8	1.1	200/200	0.001	7.2	8.7	12.5
5. SP 81.109	680m	0.04	131	0.10	318	3.617	7.4	0.8	300/300	0.01	6.8	11.2	1.1
6. SP 81.112	620m	0.42	125	0.86	257	4.833	11.7	1.3	300/300	0.001	7.2	8.9	6.5
7. SP 81.113	2963m	1.33	399	1.15	344	4.833	23.4	1.6	300/300	0.001	6.8	6.6	11.5
8. SP 81.114	2350m	0.57	170	0.70	208	4.894	20.0	2.1	300/300	0.001	6.2	7.6	5.2
9. SP 81.115	2340m	0.64	192	1.18	354	4.894	13.2	1.2	300/300	0.001	5.4	7.0	8.8
10. SP 81.116	1350m	0.63	190	1.48	445	4.894	10.4	0.9	300/300	0.001	4.9	7.6	11.0
11. SP 81.117	2165m	0.50	151	0.50	151	4.586	22.8	2.7	300/300	0.001	8.4	7.7	4.0
12. SP 81.118	1500m	0.49	146	0.77	231	4.586	14.4	1.6	300/300	0.001	7.8	9.5	6.1
13. SP 81.120	930m	0.70	212	1.54	461	5.197	11.9	1.0	300/300	0.001	5.3	6.9	10.8
14. SP 81.121	1290m	0.15	448	0.53	1607	6.461	9.0	0.5	300/300	0.01	4.7	6.0	3.0
15. SP 81.125	1490m	0.35	702	0.69	1398	6.461	16.2	0.9	200/200	0.01	4.0	5.4	3.9
16. SP 81.126	2480m	0.16	318	0.38	767	6.461	13.3	1.0	200/200	0.01	8.7	10.0	2.2
17. SP 81.128	2150m	1.62	324	4.92	985	6.461	10.6	0.7	200/200	0.001	4.9	8.1	27.8
18. SP 81.129	1140m	0.93	280	3.87	1161	6.461	7.8	0.6	300/300	0.001	5.9	6.9	21.8
19. SP 81.130	2490m	1.22	367	2.83	850	5.197	11.2	0.8	300/300	0.001	5.2	6.8	19.9
20. SP 81.131	940m	0.45	134	0.96	288	5.388	12.5	1.3	300/300	0.001	5.5	8.0	6.5
21. SP 81.132	960m	0.38	115	0.81	243	5.388	12.7	1.5	300/300	0.001	6.6	9.0	5.5
22. SP 81.134	2510m	0.65	196	1.36	409	5.942	14.2	1.3	300/300	0.001	4.7	6.5	8.4
23. SP 81.139	1600m	0.21	422	1.04	2091	5.942	6.0	0.4	200/200	0.01	4.5	6.3	6.4
24. SP 81.143	2260m	0.62	186	1.07	322	5.388	15.5	1.5	300/300	0.001	5.8	7.0	7.2
25. SP 81.145	1100m	0.44	132	0.83	249	5.229	13.8	1.5	300/300	0.001	8.7	12.2	5.8
26. SP 81.146	1880m	0.38	115	1.06	318	5.942	10.7	1.2	300/300	0.001	6.1	10.0	6.5
27. SP 81.149	1730m	0.51	153	1.29	386	5.942	11.7	1.2	300/300	0.001	4.8	7.3	8.0
28. SP 81.150	1510m	0.50	150	1.45	435	5.659	9.7	1.0	300/300	0.001	4.8	7.6	9.3
29. SP 81.151	1310m	0.49	149	1.71	514	5.659	8.2	0.8	300/300	0.001	4.8	8.1	11.0
30. SP 81.152	880m	0.31	942	1.17	3520	5.659	7.5	0.3	300/300	0.01	2.2	3.2	7.5
31. SP 81.153	900m	0.08	286	0.22	772	5.659	10.4	0.8	350/350	0.01	3.7	5.9	1.4
32. SP 81.156	950m	0.31	92	0.50	149	5.229	16.1	2.2	300/300	0.001	8.4	10.7	3.5
33. SP 81.159	2240m	0.86	257	1.30	390	5.416	17.8	1.5	300/300	0.001	6.3	6.6	8.8
34. SP 81.160	1190m	0.32	95	0.74	221	5.416	11.6	1.5	300/300	0.001	7.8	10.6	5.0
35. SP 81.162	900m	0.49	149	1.75	525	6.225	8.8	0.8	300/300	0.001	4.9	8.3	10.3
36. SP 81.163	2430m	0.61	244	1.64	656	6.225	11.5	0.9	400/400	0.001	4.1	6.8	9.6
37. SP 81.164	2170m	0.58	173	1.51	454	5.998	11.4	1.0	300/300	0.001	5.4	7.6	9.2
38. SP 81.165	1800m	0.26	385	0.82	1236	5.998	9.3	0.6	150/150	0.01	4.6	5.7	5.0
39. SP 81.166	1530m	0.45	134	0.84	253	5.998	15.8	1.7	300/300	0.001	7.0	9.0	5.1
40. SP 81.167	1000m	0.17	69	0.33	131	5.688	15.0	2.3	400/400	0.001	8.6	12.4	2.1
41. SP 81.168	1500m	0.22	62	0.43	130	5.688	13.5	2.1	300/300	0.001	9.4	12.8	2.7
42. SP 81.169	1150m	0.45	135	0.80	241	5.998	16.7	1.9	300/300	0.001	6.4	8.8	4.9
43. SP 81.170	2784m	1.06	319	1.60	482	5.760	19.0	1.5	300/300	0.001	5.2	5.7	10.1
44. SP 81.172	2430m	1.31	262	2.49	498	5.998	15.7	1.3	200/200	0.001	5.3	6.5	15.1
45. SP 81.173	1910m	0.84	253	1.59	476	5.108	13.5	1.1	300/300	0.001	4.5	6.4	11.4
46. SP 81.174	1280m	0.67	202	1.15	346	5.108	14.8	1.4	300/300	0.001	5.3	7.0	8.2
47. SP 81.175	1660m	0.59	176	1.02	307	5.380	15.4	1.5	300/300	0.001	7.9	8.4	6.9
48. SP 81.177	985m	0.26	79	0.28	83	5.380	25.5	4.1	300/300	0.001	11.4	12.8	1.9
49. SP 81.178	640m	0.38	113	0.45	136	5.640	23.4	3.0	300/300	0.001	11.1	10.6	2.9
50. SP 81.179	1130m	0.08	25	0.08	26	5.640	27.0	7.6	300/300	0.001	19.5	19.2	0.6
51. SP 81.181	950m	0.14	275	0.27	548	5.998	15.0	1.2	200/200	0.01	7.6	8.5	1.6
52. SP 81.183	830m	0.52	156	1.26	378	5.797	11.9	1.2	300/300	0.001	4.8	8.0	7.9
53. SP 81.184	1100m	1.01	304	1.72	516	5.741	16.8	1.3	300/300	0.001	4.8	5.8	11.0
54. SP 81.186	870m	0.11	212	0.22	436	6.423	15.5	1.4	200/200	0.01	7.4	10.5	1.2
55. SP 81.187	570m	0.28	84	0.57	172	5.741	13.8	1.9	300/300	0.001	10.0	10.4	3.6
56. SP 82.188	800m	0.29	117	0.16	65	6.423	57.6	9.1	400/400	0.001	12.0	8.7	0.9
57. SP 82.189	965m	0.01	49	0.04	148	6.423	10.6	1.8	400/400	0.01	8.6	14.0	0.2
58. SP 82.194	1930m	0.10	310	0.29	868	7.131	11.9	0.9	300/300	0.01	5.3	6.9	1.5
59. SP 82.195	2550m	0.04	108	0.07	216	7.131	17.7	2.1	300/300	0.01	7.5	9.9	0.4
60. SP 82.201	2180m	0.03	162	0.04	209	6.480	25.0	2.7	500/500	0.01	7.4	9.0	0.2
61. SP 82.202	2700m	0.12	480	0.12	493	6.480	31.4	2.2	400/400	0.01	7.6	6.5	0.7
62. SP 82.203	1720m	0.11	339	0.17	508	6.480	21.5	1.6	300/300	0.01	5.4	6.9	1.0

* $\sigma = T\sqrt{\frac{1}{ps} + \frac{1}{pi} + (\text{error of neutron dose})^2}$

** $U = \frac{pi(\text{tracks/cm}^2 \cdot 10^5)}{D \cdot C}$ whereby $C = 2 \cdot 74 \cdot 10^{-14}$ (factor given by STORZER, pers.comm. 1982)

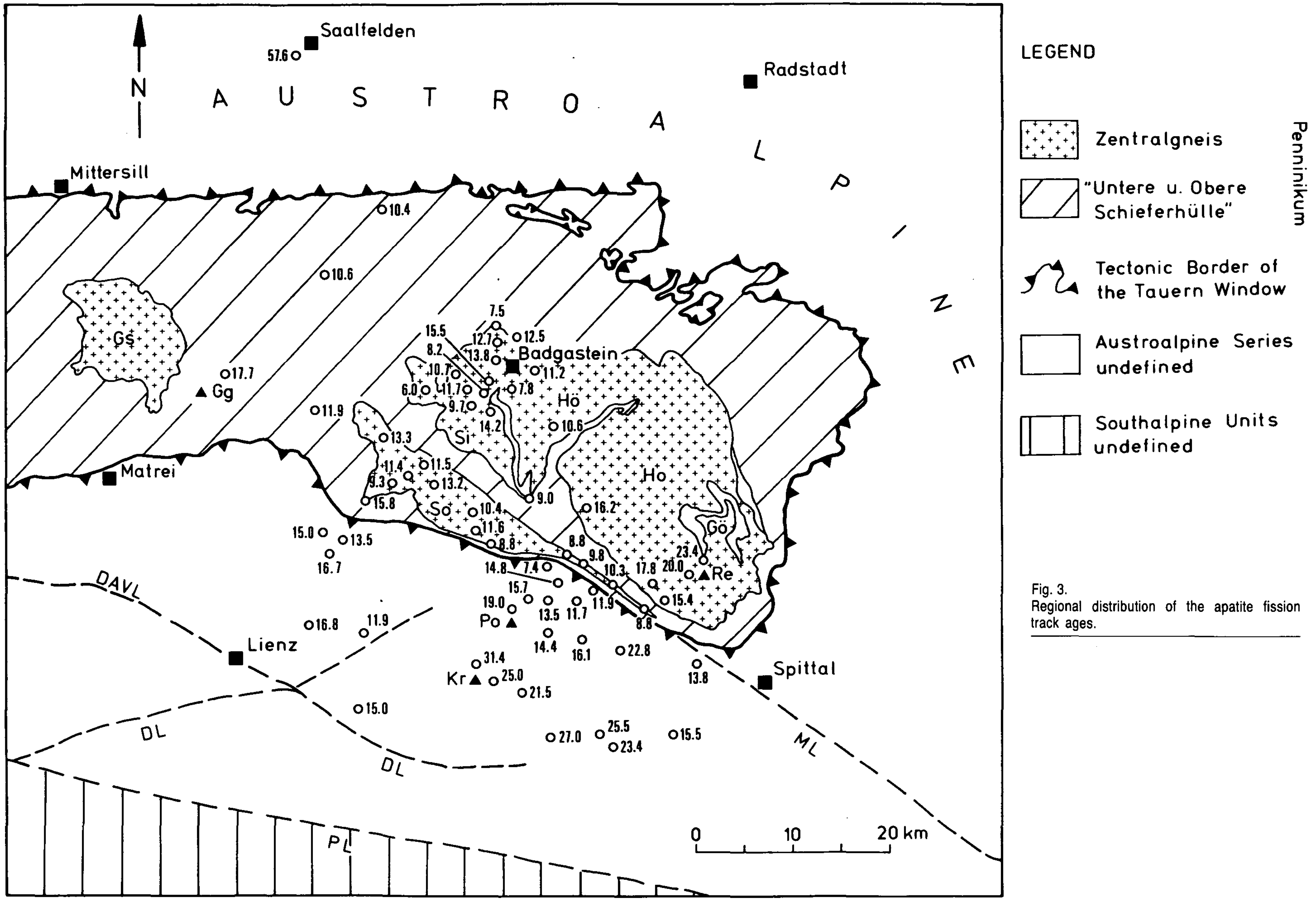

Fig. 3.
Regional distribution of the apatite fission track ages.

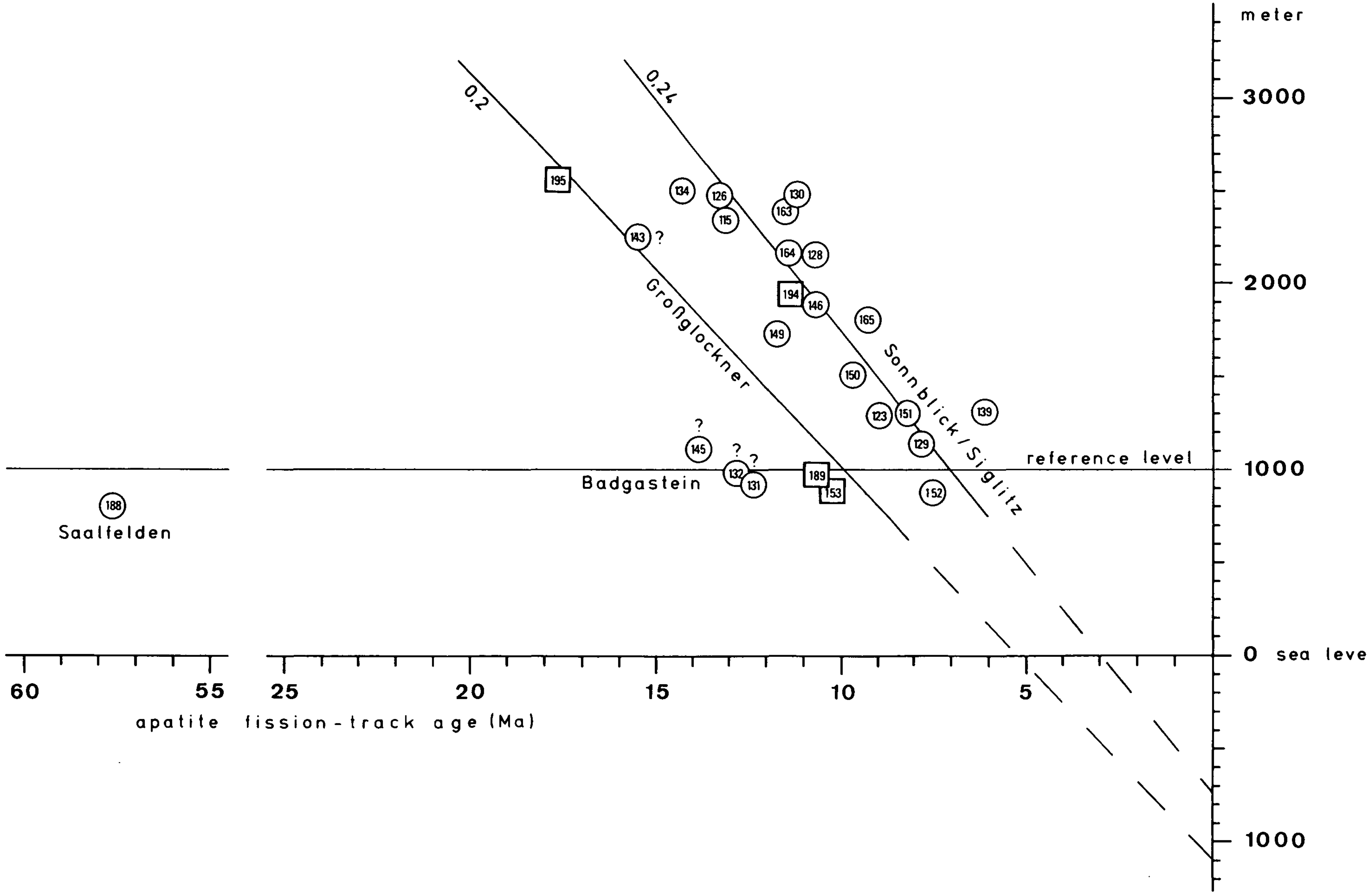

Fig. 4.
Elevation of the sampling points versus the corresponding apatite fission track ages of the Sonnblick/Siglitz area (○), Großglockner (□) and Badgastein (?).
The uplift rates are given in mm/a.

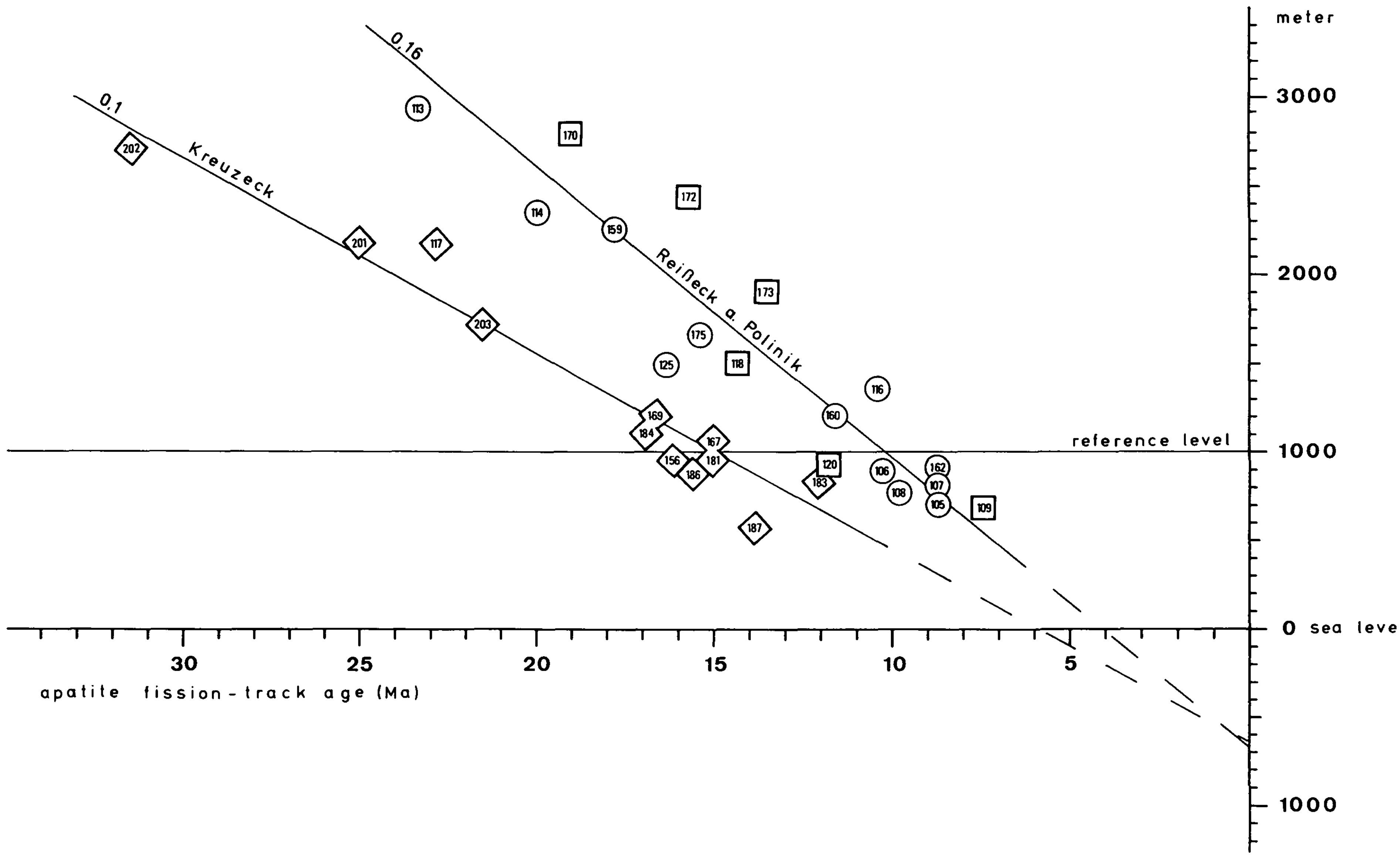

Fig. 5.
Elevation of the sampling points versus the corresponding apatite fission track ages of the profiles Reißeck (○), Polinik (□) and Kreuzeck (◇).
The uplift rates are given in mm/a.

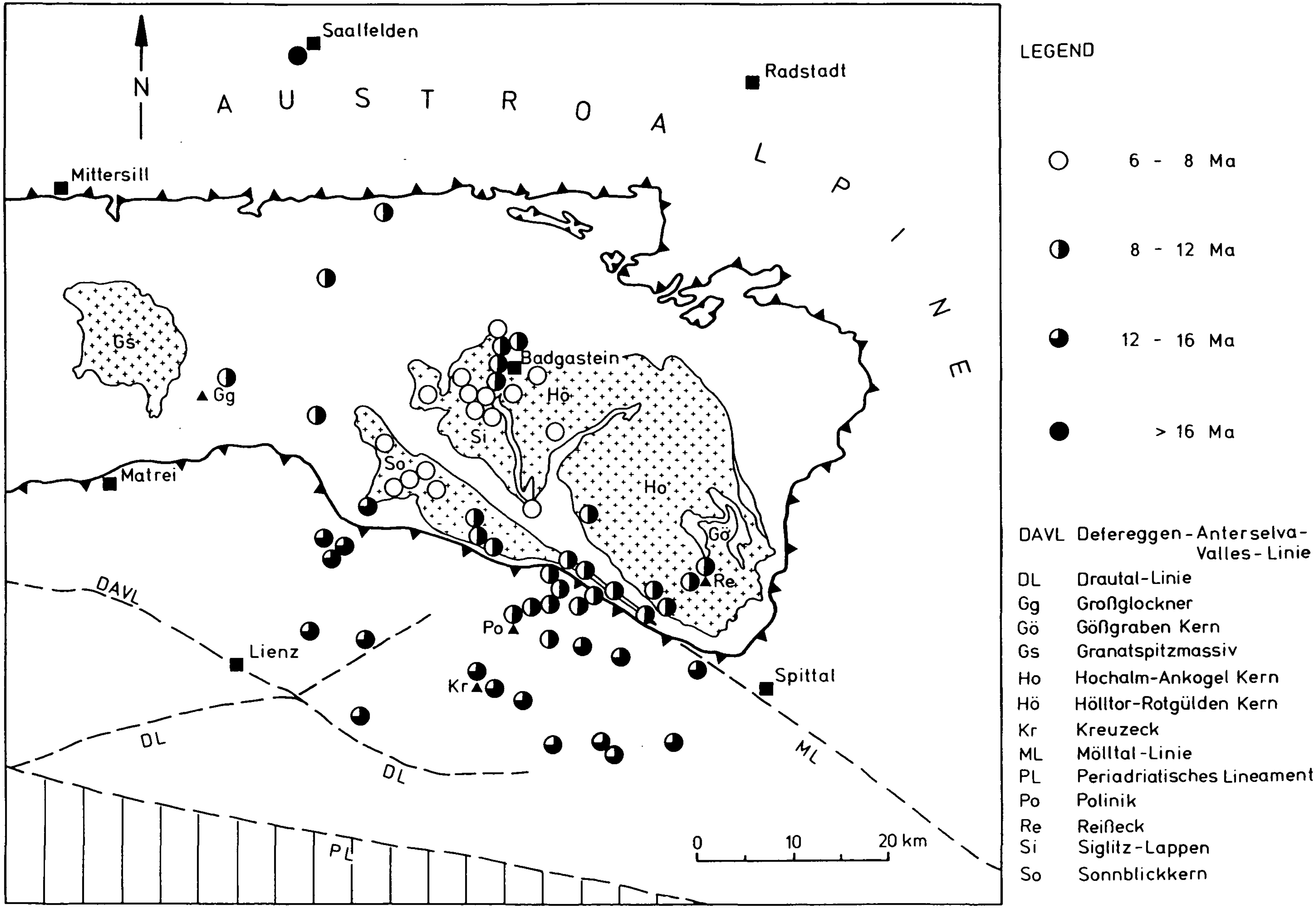

Fig. 6.
The real distribution of the fission track ages after reduction to a reference level of the 1000 m above sea level.

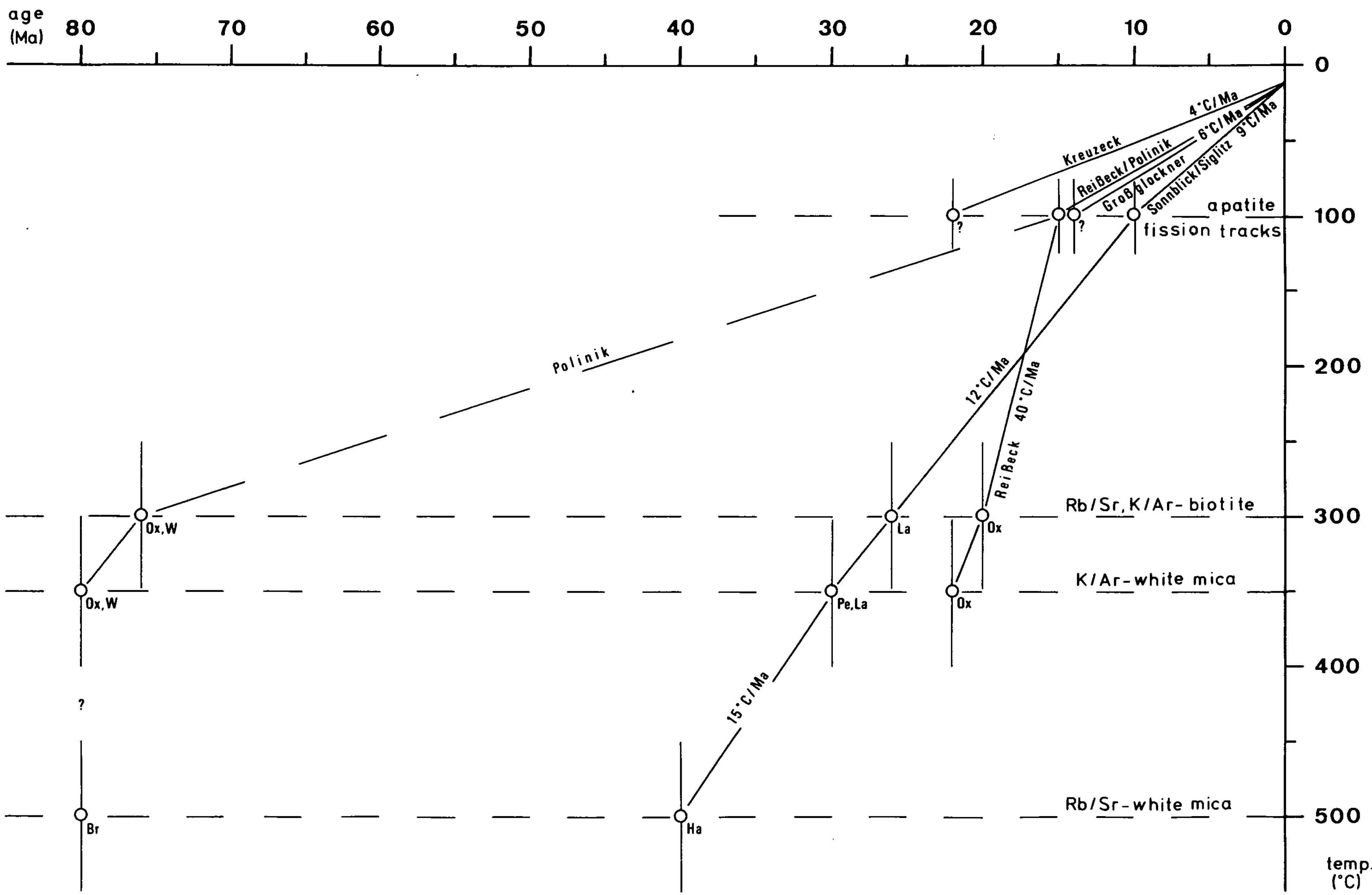

Fig. 7.
Cooling history of the eastern Tauern Window deduced from different age determination methods. The values are referred to the reference level of 1800 m above sea level.
Ox = OXBURGH et al. (1966); La = LAMBERT (1970); Pe = PEER & ZIMMER (1980); Ha = HAWKESWORTH (1976); Br = BRACK (1977).

give the resulting uplift rates in millimeters per year. These uplift rates are only valid for the time span covered by the fission track ages used.

The Sonnblick/Siglitz area shows, with 0.24 mm/a, a similar uplift rate to the Großglockner profile with 0.2 mm/a (see Fig. 4). For the Großglockner profile only 4 samples were useful for dating and therefore the calculated uplift rate should be interpreted with care.

Inside the Sonnblick/Siglitz area the samples 131, 132, 143 and 145 situated near Badgastein (in fig. 4 signed with ?) give significantly higher ages.

In fig. 5 data of the Reißeck- and Polinik-profiles are given. There is no clear difference between the calculated regression lines. Therefore a common mean uplift rate of both profiles is 0.16 mm/a.

A relatively low uplift rate of 0.1 mm/a was calculated for the Austroalpine "Altkristallin" of the Kreuzeck area (see fig. 5).

Together the data show an increase in uplift rates from the southern Austroalpine "Altkristallin" to the central Tauern Penninikum with rates of 0.1 mm/a to 0.24 mm/a.

For a better discussion of the regional uplift pattern it is useful to eliminate the dependence of the fission track ages on the elevation of the sampling points. Following a suggestion of WAGNER et al. (1977) a reference elevation of 1000 m above sea level was chosen. The intersection of the regression lines with the line at 1000 m elevation (see figs. 4 and 5) gives the time at which sample groups of identical uplift passed through the 100°C isotherm. The areal distribution of the reduced fission track ages is given in fig. 6 with following time intervals: 6–8, 8–12, 12–16 and older than 16 Ma. Like the uplift rates the reduced ages increase from the southern Austroalpine "Altkristallin" to the central Tauern Penninikum. With the exception of the Badgastein "anomaly" the youngest ages are found inside the central "Zentralgneis" of the Sonnblick/Siglitz area.

Combining the available Rb/Sr and K/Ar radiometric age data with the apatite fission track data the cooling history of the area from about 500°C to the present surface temperature is obtained. In all those cases where the altitude of the samples collected is given, the published Rb/Sr and K/Ar age data show no clear age-altitude relationship. Furthermore, the K/Ar, Rb/Sr ages for biotite and the K/Ar ages of muscovite from the Reißeck and Polinik area (OXBURGH et al., 1966; LAMBERT, 1970; WATERS, 1976) show no significant differences despite the different closure temperatures in the systems. An explanation of this fact may be that the closure temperatures are inaccurate, or, as suggested by CLIFF & OXBURGH (1971), the area experienced a very rapid cooling. Surprisingly, the Rb/Sr white mica ages of BRACK (1977) from the Altkristallin Schobergruppe are almost the same as the K/Ar white mica ages of OXBURGH et al. (1966) and WATERS (1976).

In order to combine the Rb/Sr-K/Ar cooling ages with the apatite fission track ages, only those data were included which came from samples near to each other and, where possible, from the same topographic elevation. An elevation of 1800 m was chosen as it encompasses most published data and allows a direct comparison with the results of GRUNDMANN & MORTEANI (1985) from the western Tauern Window.

In Fig. 7 the apatite fission track ages with published Rb/Sr and K/Ar cooling ages from muscovite and biotite are plotted against the corresponding closure temperatures from the different systems. Subject to the uncertainties in the closure temperature and dating techniques, this diagram gives the cooling rates for the areas considered. Thus it is apparent that the Austroalpine "Altkristallin" cooled relatively slowly, and, having reached 100°C, cooled further at the same rate (6°C/Ma) as the Penninic Tauern Window (Reißeck area). The Reißeck area experienced a very rapid cooling rate of 40°C/Ma before reaching 100°C, after which it cooled at about 6°C/Ma. The Sonnblick/Siglitz area underwent a relatively constant cooling from 15°C/Ma to 9°C/Ma.

4. Discussion

The distribution of the elevation-corrected fission track ages (fig. 6) shows a good overall agreement with the tectonic structure of the Tauern Window. The ages derived from both the Penninic rocks of the Tauern Window and the Austroalpine "Altkristallin" are interpreted as cooling ages from the late Alpine "Tauernkristallisation". They correspond to the slow-cooling model (B) of WAGNER (1979), which is typical for regional metamorphic terranes like the Tauern Window. The one exception is sample Sp 82.188 from Saalfelden, which gives an age of 57.6 Ma. This age probably represents cooling from the Early Alpine anchimetamorphism (SCHRAMM, 1980; COLINS et al., 1980), whose peak was estimated by KRALIK (1983) between 185 and 92 Ma. It may of course also represent a mixed cooling age from the Early and Middle Alpine metamorphic events. The supposition of a late Alpine (20 Ma) metamorphic event by SCHRAMM (1980) seems unrealistic in this area in view of the relatively old apatite. A similar fission track age of 42 Ma was reported by GRUNDMANN & MORTEANI (1985) from the "Grauwackenzone" near Kitzbühel.

The apatite fission track ages from this study and from GRUNDMANN & MORTEANI (1985) show, with the exception of the Granatspitz area (discussed by GRUNDMANN & MORTEANI, 1985) and Badgastein, a uniform increase from west to east across the entire Tauern Window. The relatively higher ages of the Badgastein area could perhaps be explained by isolated downsinking. EXNER (1957) mentioned numerous faults in this area. In view of the Badgastein hydrothermal springs it was expected rather that the ages would be lowered. Fig. 8 shows the fission track ages together with all available Rb/Sr and K/Ar mica age data on an east–west profile across the Tauern Window between the Brenner and Katschberg passes. All age data have been normalised to an altitude of 1800 m above sea level. The data from the Granatspitz, Habach, Zillergrund and Tuxer Stollen areas are taken from GRUNDMANN & MORTEANI (1985). The Rb/Sr and K/Ar data from the Sonnblick/Siglitz area are from LAMBERT (1970) and the ages from the Reißeck area are from OXBURGH et al. (1966).

The clear differences of the K/Ar-mica ages as given by the last authors between the Reißeck area (Penninikum) and the Polinik area (Austroalpine "Altkristallin" along the "Mölltal" line could not be demonstrated from the apatite fission track ages (see also fig. 5). If vertical movements took place along this tectonic line

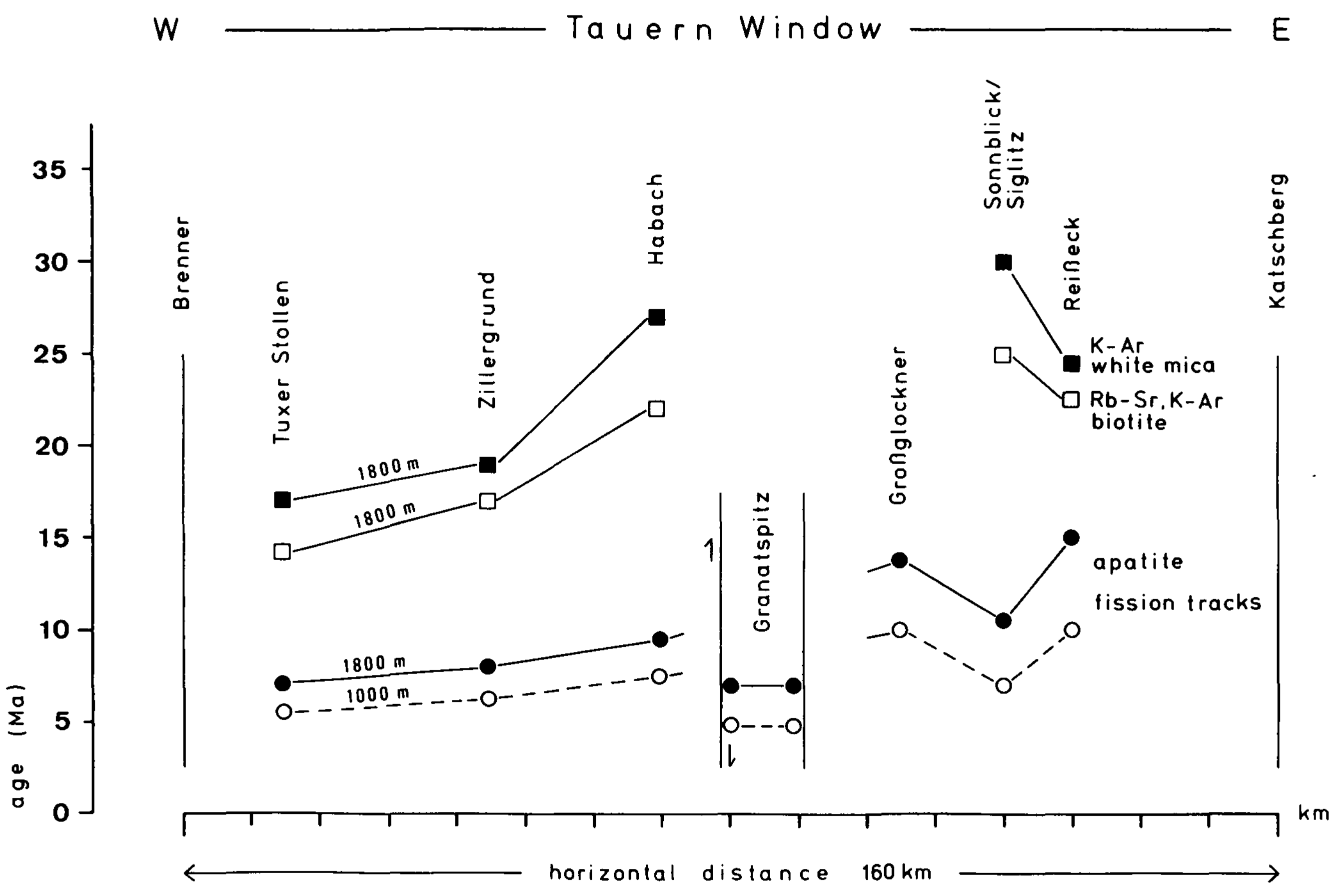

Fig. 8.
Apatite fission track ages and K/Ar, Rb/Sr mica ages as given by LAMBERT (1970) and OXBURGH et al. (1966). The dates west of the Großglockner are taken from GRUNDMANN & MORTEANI (1985).

they must be older than the fission track ages but younger than the K/Ar mica ages.

In contrast to the fission track ages, the calculated uplift rates across the entire Tauern Window decrease from west to east. Fig. 9 summarizes all uplift data from within the Tauern Window with the profiles "Tuxer Stollen" and "Habachtal" from GRUNDMANN & MORTEANI (1985). The uplift rates decrease from 0.5 mm/a in the west to 0.15 mm/a in the east. In the western Tauern Window the 100°C isotherm was crossed later than in the east, but due to a higher uplift rate in the west the same metamorphic level is exposed in both areas. After passing the 100°C level the uplift rates across the Tauern Window were uniform. In the Reißeck area CLIFF et al. (1985) showed, from Rb/Sr biotite age data along the Malta tunnel, that no „resolvable differential movements" had taken place since 16.5 Ma (age as referred to the Tunnel level). The cooling and uplift history reported by CLIFF et al. (1985) for the "southern flank" of the Gößkern dome (equivalent to the Reißeck profile of this study) agrees well with the results presented here.

Precision levelling measurements along the Tauern railway line by SENFTL & EXNER (1977) gave a recent uplift rate of about 1 mm/a which is unaccountably high compared with the fossil uplift rate of 0.16 mm/a calculated by apatite fission track data.

No information exists at present on the depth of the recent 100°C isotherm. Provided that the uplift rates are constant up to today it is possible to determine the depth of the present 100°C isotherm by linear extrapolation of the regression lines of the different areas (see figs. 4 and 5). The intercept of the extrapolated lines with the y-axis gives the level of the present 100°C isotherm. For the areas Reißeck/Polinik, Sonnblick/Siglitz and Kreuzeck the depth of the 100°C isotherm is about 700 m above sea level and for the Großglockner area it is possibly about 100 m. Based on these data the recent geothermal gradient in the former areas is 34°C/km and in the Großglockner area 31°C/km (based on the average annual surface temperature at 2200 m of 1.5°C after WAGNER et al. (1977). These estimates are in good accord with the work of CLIFF & OXBURGH (1971), who demonstrated that the metamorphic conditions in the eastern Tauern Window could be caused by an elevated geothermal gradient of 30–40°C/km. On the other hand HAENEL (1976) reported significantly lower heat flow within the Tauern Window than in its northern and southern borders. Furthermore a moderate nearsurface geothermal gradient of 16°C/km was measured in drill holes for the „Tauern Autobahn" (HAENEL, 1974). However OXBURGH & ENGLAND (1980) question the conclusion that the heat flow in the central Tauern Window is lower than in the surrounding Molasse. They point out the large correction necessary in heat flow measurements and that the near-surface measurements may be affected by ground water. This controversy can only be ended by deep drilling.

Finally of course, the question of the ultimate cause of uplift must be adressed. SELVERSTONE (1985) was able to show, through petrologic studies of the upper and lower Schieferhülle, that the uplift immediately following the "Tauernkristallisation" was due to tectonic related to continental collision. However the fact that

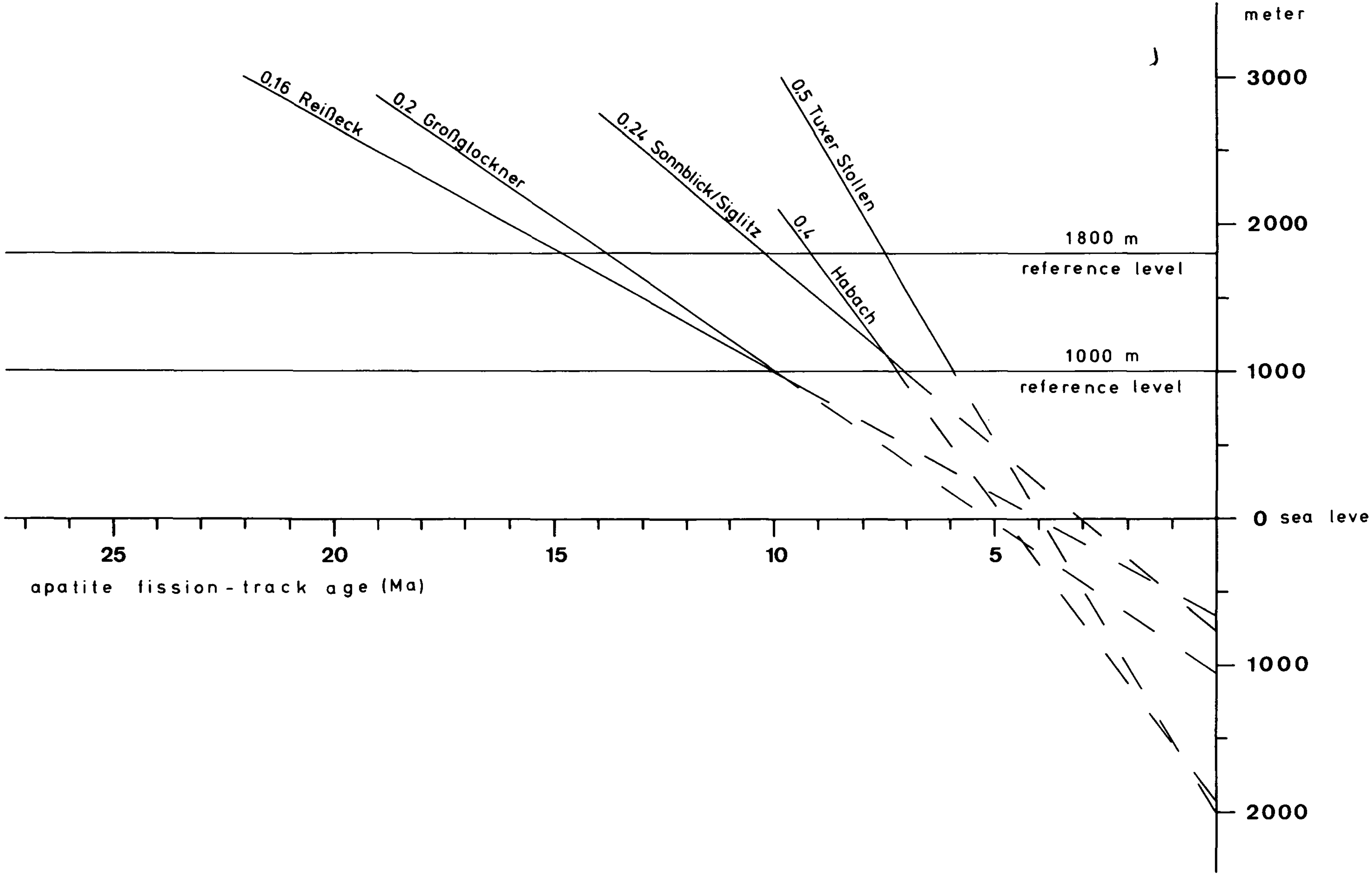

Fig. 9.
Combined diagram of the uplift profiles within the Tauern window (data from this study and, for the "Tuxer Stollen" and "Habachtal", from GRUNDMANN & MORTEANI (1985)).

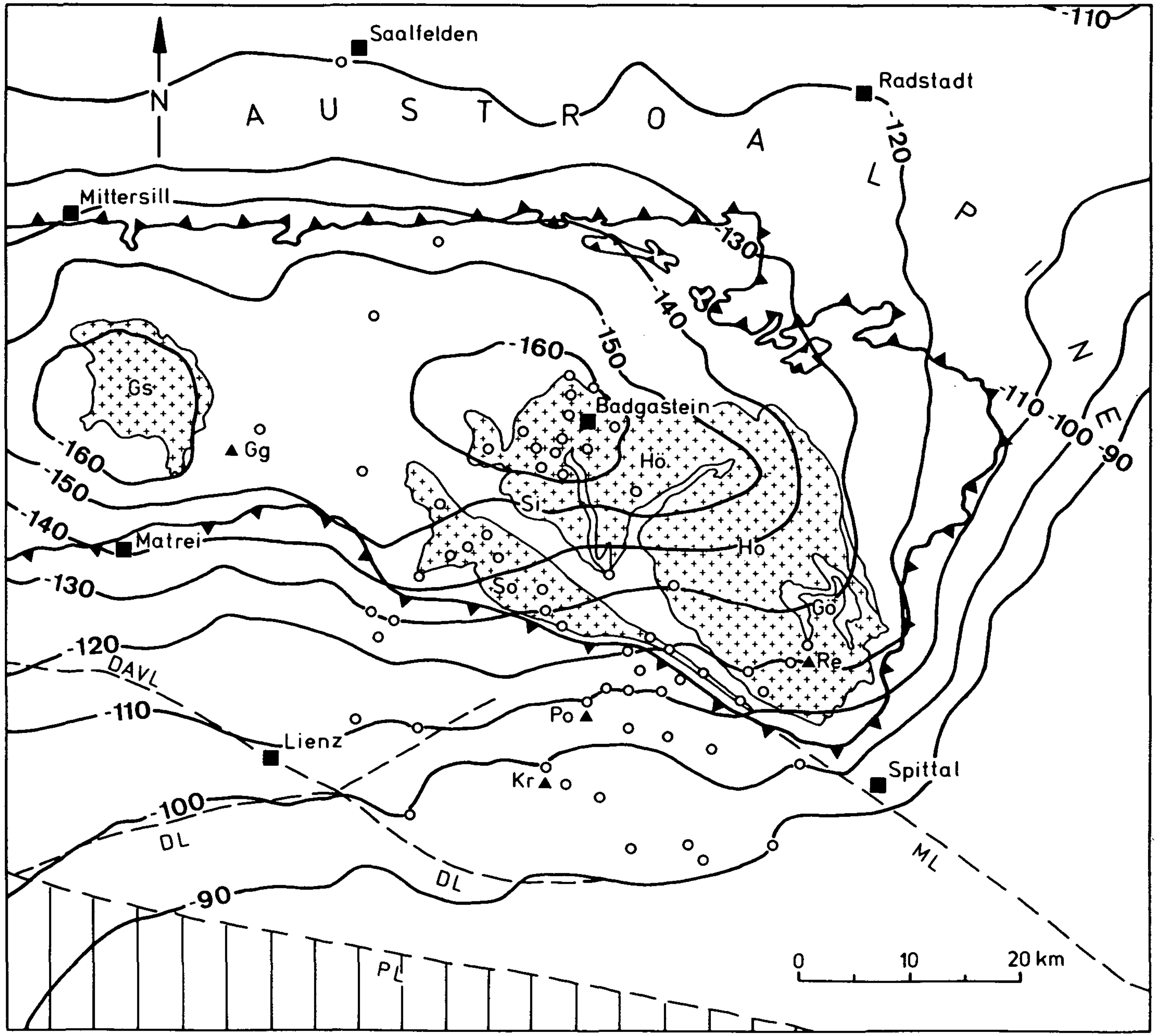

Fig. 10.
Sampling points and isogals [mgal] of the Bouguer anomalies in the investigated area according to MAKRIS (1971) and WEIHRAUCH (1983).

the different tectonic units later underwent a common pressure release suggests that isostatic adjustment is responsible for the young uplift. The regional density distribution in the investigated area can be inferred by the regional Bouguer gravity date of MAKRIS (1971) and WEIHRAUCH (1983) shown in fig. 10. A comparison of this figure with fig. 6 clearly shows that the youngest fission track ages, and thus the most rapid uplift rates coincide with the most negative Bouguer anomalies. GRUNDMANN & MORTEANI (1985) found the same relationship in the central and western Tauern Window. Since the Bouguer anomalies are a measure of the isostatic balance, the correlation of anomalies with uplift rates for the last 25 Ma suggests that the uplift was caused by deepseated density differences.

5. Conclusions

This study shows again the value of fission track age data in understandig the recent uplift and cooling history of a tectonically complex area. Together with the results of GRUNDMANN & MORTEANI (1985) we can demonstrate a uniform progression of uplift and cooling across the entire Tauern Window from 6 Ma to 23.4 Ma. It turns out that the eastern part of the Tauern Window apparently passed through the 100°C isotherm earlier than the western part, but was uplifted at a lower rate. In contrast to the heterogeneous uplift pattern in the Central Swiss Alps deduced by fission track dating by WAGNER et al. (1977), uplift of the Tauern Window was very homogeneous.

CLIFF et al. (1985), in discussing the uplift history of the south east Tauern Window in the past 25 Ma, predicted uplift rates less than 1 mm/a since 16 Ma. This was based on the fact that the average uplift rate since 25 Ma is 1 mm/a; and they could show a rapid, short-term rate of 4 mm/a from 25–20 Ma. The uplift rates reported in this study confirm their prediction. These recent, uniform uplift was probably caused by deep level isostatic adjustments.

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