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Preliminary fission-track ages on zircons and apatites from the Sardona unit, Glarus Alps, eastern Switzerland: late Miocene-Pliocene exhumation rates

by *Joanne Lihou*[1], *Anthony Hurford*[2] and *Andrew Carter*[2]

Abstract

Fission-track age determinations from a series of samples from the Infrahelvetic Sardona unit of eastern Switzerland yielded mixed Variscan and Alpine zircon fission-track ages with a mode of 160 Ma, and late Miocene-Pliocene apatite fission-track ages of 3.5 ± 0.1 Ma and 4.5 ± 0.4 Ma. These data suggest that there was an eastward younging in the onset of exhumation of material between the eastern Aar massif and the Rhine Valley. An exhumation rate of 0.8 ± 0.2 mm/yr was calculated for the region, which may be associated with a Pliocene local surface uplift maximum centred around Chur that continues to the present day. Erosional unroofing is concluded to be the principal cause for the Miocene-Recent regional exhumation of material.

Keywords: fission-track dating, exhumation, Late Miocene-Pliocene, Sardona unit, Glarus overthrust, Switzerland.

1. Introduction

The cooling pathways for rocks whose peak paleotemperature was less than 300 °C cannot be determined from conventional Rb/Sr and K/Ar radiometric dating, whose systems have closure temperatures exceeding 300 °C (HURFORD, 1991). This is why the application of the zircon and apatite fission-track techniques, which have closure temperatures of 200–250 °C and 50–120 °C, respectively (HURFORD, 1991), has been so useful in the external part of the Alps. Reviews of fission-track (F-T) methodology and analytical methods were given by HURFORD et al. (1989) and HURFORD (1991), where the ways in which these data can be used were outlined:

(i) Zircon and apatite cooling ages from the same sample can be used to derive an average cooling rate between the assumed closure temperatures for the two systems.

(ii) The distribution of confined apatite lengths is diagnostic of the style of cooling.

(iii) The present day altitude-dependence of apatite (or zircon) ages can be used to calculate an average *exhumation/denudation rate,* due to the earlier passage of a sample at a higher elevation below the closure temperature for retention of tracks.

The last method avoids having to use an estimated paleo-geothermal gradient, but assumes that the 110 °C (or 240 °C) paleo-isotherm remained horizontal and was not influenced by topography or disturbed by rapid exhumation (PARRISH, 1983). STÜWE et al. (1994) have shown that perturbation of the steady-state paleo-isotherm mirrors surface topography in a dampened fashion and is most pronounced for small wavelength, high amplitude topographic features (wavelengths of ≤ 20 km, amplitudes of ≥ 3 km). The critical isotherms also need to have resided at a constant depth relative to the earth's surface (PARRISH, 1983). If these conditions are not met, fictitious apparent exhumation rates can be produced by the downward relaxation of isotherms following a period of active tectonism, rapid uplift and erosion (PARRISH, 1983), or else the apparent exhumation rate is substantially overesti-

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mated (STÜWE et al., 1994). If these conditions are met, however, the apparent exhumation rate quantifies the approach of rocks to the earth's surface.

The most recent review and data compilation of F-T analyses in the French and Swiss Alps was made by HUNZIKER et al. (1992). The present paper adds to the data set and provides further constraints on the exhumation of the Glarus Alps and the recent updoming centred around Chur.

2. Geological setting

The *Sardona unit* of eastern Switzerland is located between Elm in Sernftal and Bad Ragaz in the Rhine valley (Fig. 1), an area of 25 × 10 km, at elevations of 500 to 2700 m. It consists of Cenomanian-Campanian pelagic limestones and marls, plus Maastrichtian to Bartonian flysch deposits (LIHOU, 1993). It is an allochthonous unit, being bounded by thrusts, which together with the underlying Blattengrat and North Helvetic Flysch (NHF) units, forms part of the *Infrahelvetic Complex.* The Infrahelvetic Complex also includes the autochthonous and parautochthonous cover to the *Aar massif,* since it comprises all the tectonic units that structurally underlie the Helvetic nappes and are separated from them by the *Glarus Overthrust* (Fig. 2). The present topography of the Glarus Overthrust is a WSW–ENE trending culmination, with a southern flank sloping 15–20° and a northern flank sloping 10–15° (SCHMID, 1975), that plunges gently eastwards from Vättis to the Rhine valley (TRÜMPY and TROMMSDORFF, 1980). Hence, the Sardona unit crops out in tectonic windows through the culmination in the Overthrust (Fig. 1).

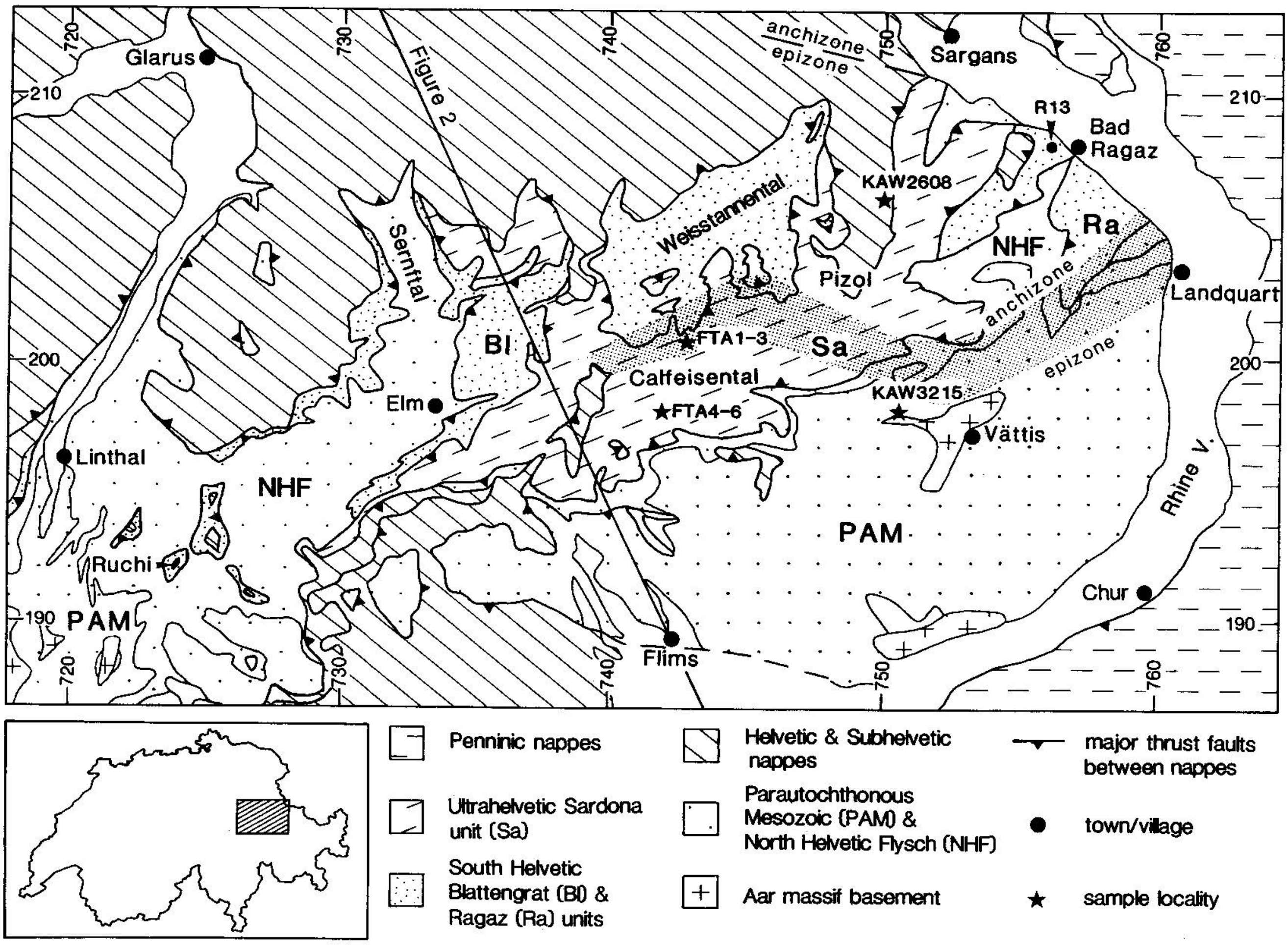

Fig. 1 Tectonic map of the Glarus Alps, eastern Switzerland, adapted from TRÜMPY (1967) and SPICHER (1980), also showing the line of cross-section for figure 2, fission-track sample localities and the anchizone/epizone boundary within the Infrahelvetic Complex (shaded area) compared with its location in the Verrucano of the Glarus (Helvetic) nappe (dashed line), taken from WANG et al. (1995); marginal numbers refer to the Swiss coordinate system and are marked at intervals of 10 km.

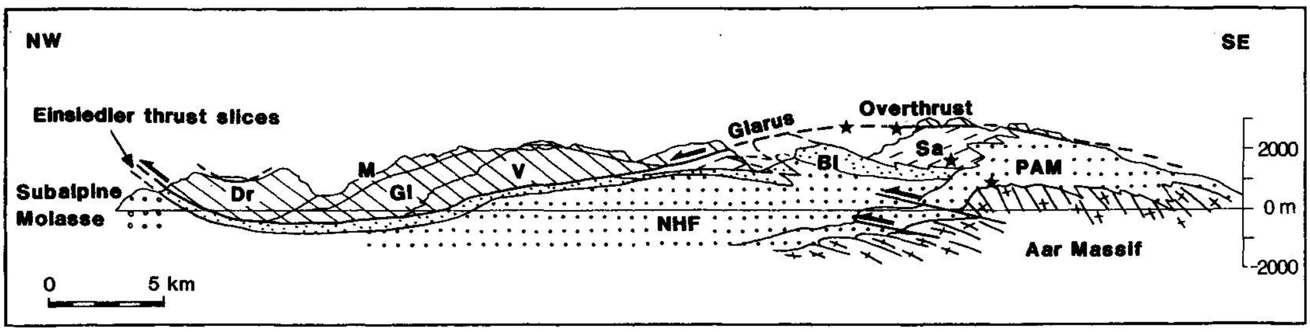

Fig. 2 Simplified true scale structural cross-section through the Glarus Alps, eastern Switzerland, modified from TRÜMPY (1980) and PFIFFNER (1986) showing the projected positions of fission-track sample localities; key as in figure 1.
Bl – Blattengrat unit; Dr – Drusberg nappe; Gl – Glarus nappe; M – Mürtschen nappe; NHF – North Helvetic Flysch unit; PAM – Parautochthonous Mesozoic; Sa – Sardona unit; V – Verrucano.

3. Regional review of Alpine metamorphism and exhumation history

The Helvetic zone and Infrahelvetic Complex were deformed during the Neo-alpine Orogeny (Oligocene-Miocene). The deformation was subdivided into four phases by MILNES and PFIFFNER (1977, 1980): the Pizol, Cavistrau, Calanda and Ruchi phases. Burial by Penninic and Austroalpine nappes led to *very low grade metamorphism* in the Infrahelvetic Complex and the Helvetic nappes (FREY et al., 1973, 1980; GROSHONG et al., 1984). A variety of methods have been used to quantify the degree of incipient metamorphism and thus unravel the tectonothermal evolution: critical mineral assemblages, illite "crystallinity", coal rank and fluid inclusion microthermometry. The techniques involved are reviewed in FREY (1986).

Early work using these techniques in the Helvetic Alps established that metamorphic zones ran parallel to the Alpine border, increasing in grade from north to south, from diagenetic grade at the Alpine border, to anchizone-epizone in the par-autochthonous cover to the Aar massif, and downwards in the nappe pile (FREY et al., 1973, 1980; GROSHONG et al., 1984). Moreover, the same work showed that metamorphic zones cross-cut tectonic boundaries, implying that the metamorphism was post-tectonic and was related to burial of the nappe pile and concomitant heating. In addition, a discontinuity in the metamorphic gradient was identified across the Glarus Overthrust, at the contact between the Helvetic nappes and the Infrahelvetic flysch units (FREY et al., 1980; FREY, 1988).

Recent, local metamorphic studies have focused on the Infrahelvetic flysch units (ERDELBROCK, 1994; RAHN et al., 1994, 1995; WANG et al., 1995). By mapping iso-reflectance lines derived from vitrinite reflectance values, RAHN et al. (1995) and ERDELBROCK (1994) were able to estimate the amount of post-metamorphic horizontal offset across the Glarus Overthrust to be in the order of 5–10 km. WANG et al. (1995) also found that the offset of illite "crystallinity" zones was ~10 km (Fig. 1). Peak metamorphic temperatures were gauged directly from the temperature of homogenization of fluid inclusions, and also from vitrinite reflectance data using the calibration technique of BOSTICK et al. (1978), which depends on the effective heating time (t_{eff}) (i.e., the duration of burial of a rock within 15 °C of its peak temperature). RAHN et al. (1994) found that paleotemperatures of 270–310 °C for the NHF unit in Linthal (Fig. 1) derived by the two methods, were concordant when the t_{eff} was assumed to be 1 Myr. ERDELBROCK (1994) also concluded that there had been a very short heating time of no more than 1 Myr, during which paleotemperatures reached 300–320 °C in the Sardona unit in Calfeisental (Fig. 1).

Dating of Alpine metamorphism has been constrained by Rb/Sr and K/Ar dating of radiogenic minerals, a review of which was made by HUNZIKER et al. (1992). Metamorphism in the Helvetic nappes was dated as early to middle Oligocene (30–35 Ma), from concordant K/Ar and Rb/Sr mineral ages, with a second, Miocene metamorphic phase at 20–25 Ma affecting the Infrahelvetic Complex (HUNZIKER et al., 1986). The timing of the earlier metamorphism, which post-dates Calanda phase emplacement of the Helvetic nappes onto the Infrahelvetic Complex (GROSHONG et al., 1984), is further constrained by the age of the youngest metamorphosed sediments found in the Infrahelvetic Complex (i.e., the Engi slates of the NHF unit) of early Oligocene age, and the first appearance of diagenetic grade metamorphosed Helvetic pebbles in the Upper Marine Molasse of mid Miocene age (HOMEWOOD et al., 1986; HUNZIKER et al., 1986). Geochronological ages for the younger metamorphism may be as young as 14 Ma (HUNZIKER, in PFIFFNER, 1986) and would therefore indicate that post-metamorphic, Ruchi phase, movements on the Glarus Overthrust are post-mid Miocene.

MICHALSKI and SOOM (1990) reconstructed the *cooling and exhumation history* of the basement of the Helvetic zone, the Aar and Gotthard massifs, using the fission-track technique, incorporating new and previously-published data. They concluded that cooling in the east of the Aar massif began in the early Miocene, where zircon cooling ages ranged from 19–27 Ma. Confined track lengths in the apatites, of 13.5–14.5 μm, were interpreted as indicating undisturbed steady cooling. Apatite ages gave an exhumation rate of 0.3–0.5 μm/yr from 10–5 Ma (i.e., during the late Miocene).

RAHN (1994) measured apatite F-T ages for 14 samples from the NHF unit, the parautochthonous cover to the Aar massif, in a profile from Linthal (725 m) to the Ruchi mountain (3100 m) (Fig. 1). The apatite ages ranged between 5.4 and 8.6 Ma, i.e., mid-late Miocene, and showed a strong altitude-dependence, from which an exhumation rate of 0.65 mm/yr was calculated. An interesting result was the discontinuity in the apatite ages at the Glarus Overthrust, which may indicate that there has been movement along this thrust since the late Miocene.

4. Aims and methods

A preliminary F-T study in the Sardona unit was undertaken in order to corroborate the results of MICHALSKI and SOOM (1990) and RAHN (1994). Three samples were collected from the *Sardona Quartzite Formation* at each of two localities in Calfeisental (Fig. 1). This Formation is a Paleocene to early Eocene arenitic flysch unit, that also includes a debris flow conglomerate, the *Crystalline Conglomerate,* containing many exotic sedimentary and crystalline clasts probably from the Austroalpine and Penninic realm (LIHOU, 1993). At each locality, samples of the Sardona Quartzite, the matrix to the Crystalline Conglomerate and a granitic clast from the Crystalline Conglomerate were collected. In this way, concordant ages from a particular locality would increase confidence in the results. It was also hoped that the granitic clasts would yield either Alpine zircon F-T cooling ages, or else pre-Alpine cooling ages that would answer some petrological questions as to its origins.

In addition, one sample was collected from the *Guschakopf Sandstone,* of the Ragaz unit, at much lower elevations in the Rhine Valley. This sandstone is probably a lateral equivalent to the Sardona Quartzite.

Samples for *F-T analysis* were prepared from heavy mineral concentrates of apatite and zircon. Spontaneous fission-tracks were revealed in polished mounts of apatite using 5N HNO_3 at 20 °C for 20 seconds, and of zircon using a binary eutectic of KOH : NaOH at 225 °C for 20–36 hours. Irradiation of the samples with thermal neutrons was made at the thermal facility of the Risø Reactor at the National Research Centre, Roskilde, Denmark. Induced tracks were recorded in mica external detectors and the fluence monitored using Corning glass dosimeters CN-5 (~ 11 ppm U) for apatite and CN-2 (~ 36 ppm U) for zircon irradiations. Mica detectors were etched in 40% HF at 20 °C for 40 minutes. Tracks were counted using Zeiss Axioplan microscopes with ×100 objectives and a maximum magnification of ×1250. Central ages were calculated using the IUGS-recommended zeta calibration approach (HURFORD, 1990).

5. Results

F-T central ages are presented in table 1. The granite clasts (FTA 1 and 6) gave essentially the same zircon age of about 165 Ma. Central zircon ages from the Sardona Quartzite and the Guschakopf Sandstone had a much wider range of ~ 99–208 Ma. Insufficient apatite crystals were retrieved from the Guschakopf Sandstone to yield an age. However, the samples at each locality in Calfeisental (FTA 1–6) yielded concordant apatite ages, increasing confidence in the results (Tab. 1). Taking an average age for each locality, the apatite ages from the Sardona unit are 3.5 ± 0.1 Ma and 4.5 ± 0.4 Ma (i.e., late Miocene-Pliocene), and are therefore much younger than the mid-late Miocene ages obtained by RAHN (1994) from the NHF unit, 20 km to the west, and by MICHALSKI and SOOM (1990) from the Aar and Gotthard massifs 65 km to the southwest. However, the apatite ages from the Sardona unit are similar to the young 4.5 ± 1.2 Ma age obtained by MICHALSKI and SOOM (1990) from a nearby locality at Vättis (Fig. 1, Tab. 1). This suggests that there may be an eastward younging in the apatite ages that mirrors the westward younging identified by MICHALSKI and SOOM (1990) at the western end of the Aar massif.

Tab. 1 Fission-track apatite and zircon analytical data for the Calfeisental-Rhine valley region. Notes:
(i) H (m) is the perpendicular distance to the Glarus Overthrust calculated from the structure contour map of SCHMID (1975);
(ii) analyses were made by the external detector method using 0.5 for the $4\pi/2\pi$ geometry correction factor;
(iii) track densities (ρ) are quoted as $\times 10^6$ tracks cm^{-2} and N is the total number of tracks counted;
(iv) $P\chi^2$ is the probability of obtaining χ^2 value for v degrees of freedom, where v = no. crystals – 1;
(v) ages of FTA samples were calculated using dosimeter glass CN-5 (apatite) with ζCN5 = 339 ± 5, and CN-2 (zircon) with ζCN2 = 124 ± 5, calibrated by multiple analyses of IUGS apatite and zircon age standards (see HURFORD, 1990);
(vi) the central age is a modal age, weighted for different precision of individual crystals (see GALBRAITH, 1992);
(vii) KAW samples are from MICHALSKI and SOOM (1990); these authors do not quote the number of crystals used to derive their zircon central age for sample KAW 3215.

Sample no. Rock type	Locality	Elevation (m) H (m)	mineral	No. of crystals	Dosimeter ρ_d	Dosimeter N_d	Spontaneous ρ_s	Spontaneous N_s	Induced ρ_i	Induced N_i	Age Dispersion χ^2	Age Dispersion %	Age (Ma) ± 1σ
KAW 2608	Schwarze Hörner	2400	apatite	10	7.43	5744	0.7	18	13.2	320	< 2	–	6.4 ± 1.7
Verrucano cgl	(749.75/205.75)	+300	zircon	3	6.02	5271	138.0	361	55.0	144	15	–	96 ± 1.0
FTA 1	Heubützlipass	2400	apatite	10	1.347	9337	0.022	9	1.242	508	< 1	107	4.0 ± 1.4
Granite clast	(741.5/200.7)	–350	zircon	12	0.475	3289	24.76	2299	4.458	414	< 1	24.7	161 ± 15
FTA 2	Heubützlipass	2400	apatite	10	1.347	9337	0.818	44	3.715	1998	70	0.03	5.0 ± 0.8
Cgl matrix	(741.5/200.7)	–350	zircon	–	–	–	–	–	–	–	–	–	–
FTA 3	Heubützlipass	2400	apatite	9	1.199	8306	0.065	13	2.886	580	80	0.0	4.6 ± 1.3
Quartzite	(741.5/200.7)	–350	zircon	16	0.475	3289	27.10	3381	3.688	460	< 1	66.8	208 ± 36
FTA 4	Troseggtobel	1830	apatite	–	–	–	–	–	–	–	–	–	–
Quartzite	(741.8/198.0)	–1270	zircon	11	0.475	3289	17.49	1745	5.061	505	< 1	31.6	99 ± 11
FTA 5	Troseggtobel	1830	apatite	20	1.199	8306	0.050	43	3.089	2642	15	39.7	3.4 ± 0.6
Cgl matrix	(741.8/198.0)	–1270	zircon	–	–	–	–	–	–	–	–	–	–
FTA 6	Troseggtobel	1830	apatite	20	1.199	8306	0.093	70	5.273	3961	30	18.9	3.6 ± 0.4
Granite clast	(741.8/198.0)	–1270	zircon	19	0.475	3289	20.02	3302	3.480	574	< 1	52.4	169 ± 22
KAW 3215	Vättis	1060	apatite	10	7.81	4871	0.58	14	15.7	374	7	–	4.5 ± 1.2
mylonite	(751.30/197.70)	–2140	zircon	?	9.24	4461	1.0	29	24.4	82	69	–	19.1 ± 4.2
R13	Bad Ragaz	600	apatite	–	–	–	–	–	–	–	–	–	–
Sandstone	(756.3/208.1)		zircon	20	0.475	3289	19.81	2746	3.723	516	< 1	80.5	147 ± 28

No track length data from the apatite samples is available because of low spontaneous track densities.

6. Discussion and interpretation

6.1. ZIRCON AGES

The concordance of zircon central ages for the granite clasts implies that either they have the same provenance or the same thermal history. Examination of a radial plot for sample R13 from the Guschakopf Sandstone (Ragaz unit) revealed an equivalent mode, indicated by a cluster of zircons close to 160 Ma (Fig. 3), suggesting that the sand may have been derived from weathering of the same type of granitic terrane as the clasts in the Crystalline Conglomerate. Another, 50 Ma mode (i.e., early Eocene age) in the zircon ages was obtained from 20% of the crystals analyzed and is close to the depositional age of the sandstone (Fig. 3). This age may be a true Alpine cooling age for the zircons, or alternatively, it could date the cooling of newly-formed igneous zircons. The grains possessing a 50 Ma age exhibited euhedral to subhedral morphology, suggesting that they represent first cycle detritus. WINKLER et al. (1990) obtained a central zircon age of 57.8 ± 2.7 Ma from a Paleocene bentonite horizon in the Schlieren Flysch which WINKLER (1983) concluded was derived from a subduction-related magmatic arc. The zircons from the Guschakopf Sandstone possessing a 50 Ma age could therefore have been derived from weathering of a similar volcanic source.

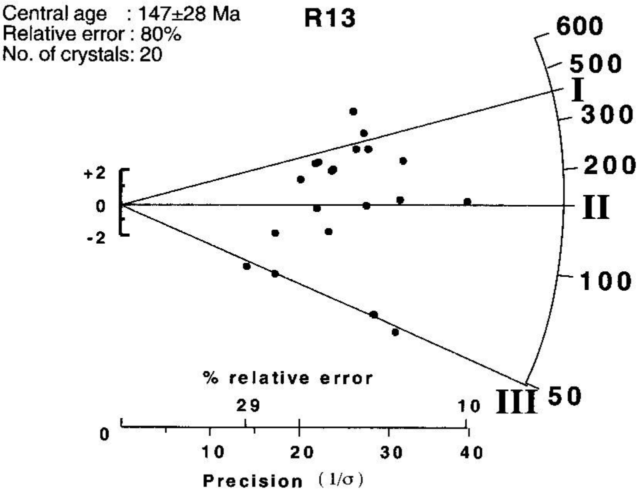

Fig. 3 Radial plot displaying individual zircon grain ages for sample R13 against a standardized error (left hand side); grains with increasing precision are closer to the radial axis on the right. This particular sample, from the early Eocene Guschakopf Sandstone, statistically comprises three age modes; (I) the oldest modal age comprises Paleozoic zircons; (II) the second modal age of ~ 160 Ma is similar to the central zircon ages of granite clasts from the Crystalline Conglomerate (FTA 1 and 6); and (III) the youngest age of ~ 50 Ma is within error of the stratigraphic age – see text for discussion.

Zircon ages in the Sardona unit are probably *mixed Variscan and Alpine ages.* MICHALSKI and SOOM (1990) also found that zircon ages north of the Aar massif were a mixture of Variscan and Alpine cooling ages, implying that the peak Alpine paleotemperature was below the closure temperature for zircon and that the tracks were therefore not completely annealed. They concluded that the temperature range for the zircon mixed age zone (or partial annealing zone) was 200–250 °C. However, ERDELBROCK (1994) determined peak paleotemperatures of 300–320 °C for this region based upon vitrinite reflectance measurements, which are well in excess of the accepted closure temperature for zircon. It must be born in mind that these vitrinite reflectance values are at the upper limit of applicability of the technique and the paleotemperatures may therefore be slightly overestimated. Nevertheless, paleotemperatures exceeding 250 °C probably were achieved since samples FTA 1–3 lie within the anchizone/epizone transition (270–310 °C, RAHN et al., 1994) and samples FTA 4–6 fall within the epizone defined by WANG et al. (1995) (Fig. 1), so the zircon fission tracks should have been reset. Hence, an alternative explanation for the mixed zircon ages in this area must be sought.

Closure temperature also depends on the cooling rate, faster cooling producing an elevated closure temperature (HUNZIKER et al., 1992). However, MICHALSKI and SOOM (1990, Fig. 11) determined a very slow initial cooling rate of 7 °C/Myr from the early Miocene to Pliocene (19.1–4.5 Ma) for a sample from Vättis (Fig. 1), although this calculation assumed that the zircon closure temperature was only 225 °C and the apatite closure temperature was 120 °C. One remaining possibility is that the *effective heating time* for the peak metamorphism was too short (~ 1 Myr – see above) for many of the zircons to have had enough time to be completely reset. Newly generated zircon annealing data at laboratory and geological timescales have revealed that for effective heating times of 10^7 yr, the zircon partial annealing zone lies between 210 °C and 350 °C, but if the heating time is reduced to 10^6 yr, the partial annealing zone is shifted to 230–370 °C (YAMADA et al., 1995; TAGAMI et al., 1995). In light of this information, minor levels of track annealing that would be expected for the Sardona samples if the effective heating time was close to 10^6 yr.

6.2. APATITE AGES

The apatite results from the Sardona unit were combined with two of MICHALSKI and SOOM'S (1990) results, from the sites at Vättis and Schwarze Hörner at the east end of Calfeisental (Tab. 1 and Fig. 1). There appears to be poor correspondence between apatite age and elevation (Fig. 4a), but better correspondence between age and perpendicular distance from the Glarus Overthrust (Fig. 4b). Sample KAW 3215 from Vättis plots to the right of the best regression line for these data, i.e., towards higher ages (Fig. 4b); its earlier cooling may have been caused by local Pliocene valley incision, when the Paleo-Rhine Valley ran through Kunkelpass, Vättis and Ragaz, only later deviating to its current course via Chur and Landquart (Adrian Pfiffner, pers. comm.; Fig. 1).

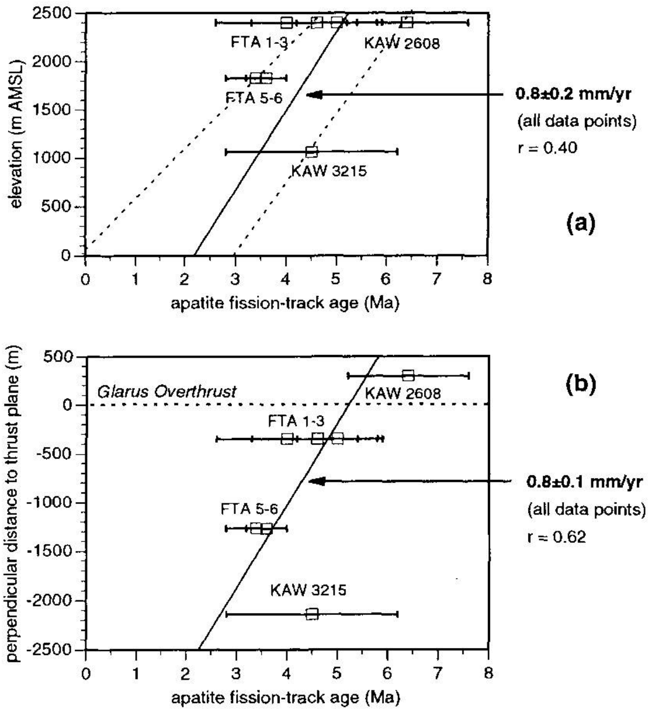

Fig. 4 (a) Scatter plot of apatite age versus elevation in the region Calfeisental-Pizol, showing poor correspondence, with sites FTA 1–3 and KAW 2608 from equivalent elevations above mean sea level (AMSL) displaying a range of central ages, although these ages could be considered equivalent within statistical error. Treating the FTA and KAW data sets separately, to take into account the geographical separation of 3–5 km between these localities and the possible effects of perturbations in the 110 °C isotherm, would result in exhumation rates of 0.6 and 0.7 mm/yr, respectively. (b) Scatter plot of apatite age versus perpendicular distance from the Glarus Overthrust in the region Calfeisental-Pizol, showing better correspondence than graph (a), although samples KAW 3215 and FTA 1–3 give the same central age, despite the fact that they reside at different distances from the Glarus Overthrust – see text for discussion.

KAW data points are taken from MICHALSKI and SOOM (1990), error bars shown are 1σ and regression lines were fitted to the data using a computer-aided graphics programme.

RAHN (1994) also reached the conclusion that there was better correspondence for his data from the NHF unit when he plotted apatite age against perpendicular distance from the Glarus Overthrust; samples varying in their perpendicular distance from the Glarus Overthrust exhibited a range of ages that could not be ascribed to differences in altitude, since they were derived from a horizontal sampling profile within Linthal. Using the Glarus Overthrust as the reference plane, an apparent uplift rate of 0.8 ± 0.2 mm/yr was generated for the data from Calfeisental-Pizol (Fig. 4b), which is greater than the rate of 0.3 ± 0.1 mm/yr generated for the NHF unit generated by the same method (RAHN, 1994), or the rate of 0.3-0.5 mm/yr for the eastern Aar massif from MICHALSKI and SOOM (1990), although this was calculated using an age-altitude relationship. Combined with the eastward younging in the apatite F-T ages, this suggests that there was later but faster exhumation of material towards the east. No displacement of the apatite ages across the Glarus Overthrust was detected, as in the case of the NHF unit (RAHN, 1994).

Despite the caution needed in interpreting apparent *exhumation rates,* the rate calculated for this study can be accepted as a reasonable value for the Glarus Alps for the following reasons. During the Alpine metamorphic phase, the Helvetic nappes and Infrahelvetic Complex were buried beneath a Penninic and Austroalpine nappe pile that was 12 km thick (GROSHONG et al., 1984). The Glarus Overthrust, which marks the boundary between these tectonic units is itself now exposed at elevations of 1000–3000 m (SCHMID, 1975), attesting to the exhumation of once-buried rock. As a horizontal feature that was independent of late Miocene-Pliocene surface topography, using the Glarus Overthrust as a reference plane for apatite fission-track dates, tests whether the 110 °C paleo-isotherm was significantly perturbed by topography on the scale of the spacing between sample sites and therefore likely to give spurious exhumation rates. The fact that a better correspondence between apatite ages and perpendicular distance from the Glarus Overthrust was observed both in this study (Fig. 4b) and that of RAHN (1994) may mean that the Glarus Overthrust was parallel to the critical paleo-isotherm, and may still have been a planar feature, only attaining its current arched geometry since 3.5 Ma. In addition, our own structural investigations of the north-dipping limb of the Glarus Overthrust near Pizol (Fig. 1) have revealed that normal displacements of up to a few metres on northward-dipping, steeply-inclined cleavage-parallel fault planes commonly affect the main thrust boundary. These minor normal faults may have accommodated arching of the Glarus Overthrust and would therefore support our hypothesis that this arching post-dates the main, Calanda phase thrust displacement. This interpretation challenges PFIFFNER'S (1985) conclusion that the Glarus Overthrust was arched by Calanda phase shortening of the Infrahelvetic Complex in its footwall.

Valley relief in Calfeisental reaches 2000 m near to its mouth at Vättis, and its separation from the adjacent, parallel valley of Weisstannental to the north is 6–10 km (Fig. 1), meaning that the present day topography can be modelled with an amplitude of 2000 m and a wavelength of 12–20 km. For a topographic wavelength of 12–20 km where perturbations of the critical paleo-isotherm existed, differences in its depth would have been important for samples separated by lateral distances of a quarter wavelength, i.e., 3–5 km; this is the spacing between sites in Calfeisental. Assuming that the current topography is a reasonable analogue for the topography of the Glarus Alps in the late Miocene-Pliocene, or at least that the area was no more rugged than at present, figure 6 of STÜWE et al. (1994) can be used to estimate the perturbation of the critical paleo-isotherm. Assuming that steady-state had been reached, a denudation rate of 0.8 mm/yr would have caused perturbations in the isotherm ranging between 200 and 500 m for a topographic wavelength of 12–20 km. From equation (4) of STÜWE et al. (1994), this range of perturbations would result in a 10–25% (± 0.2 mm/yr) overestimation in the actual exhumation rate. We do not feel that this represents a significant error in the apparent exhumation rate given the uncertainties in the fission-track analytical procedure and in view of the fact that this is the same as the error involved in the graphical calculation of the exhumation rate (Fig. 4b). We also feel that the geothermal gradients assumed in STÜWE et al.'s (1994) model may not be applicable to the Alps in the Miocene, and coupled with the gross approximations required in applying this model to the Glarus Alps, the calculation is unjustified.

Indirect evidence that uplift of the area since the early Miocene has indeed been driven by erosion of material can be provided using a simple calculation that was developed by BROWN (1991) and has been used in other mountain belts (FOSTER et al., 1994). Adopting a paleo-geothermal gradient of 35 °C/km (ERDELBROCK, 1994), and assuming a mean paleo-surface temperature of 10 °C, the depth to the pre-late Miocene 110 ± 10 °C isotherm was ~ 3000 m. Hence, the amount of material removed since the late Miocene is at least 3000 m. Added to this, localities which passed through this isotherm in the late Miocene are now elevated to ~ 2500 m (samples FTA 1–3 and KAW 2608), i.e., 500 m above the present mean surface elevation in the Glarus Alps, so an additional 500 m of material has been removed assuming that the present mean surface elevation is similar to that in the late Miocene. Therefore, at least 3500 m of regional denudation can be accounted for since the late Miocene.

Tectonic uplift of the Aar massif and its cover nappes was initially accommodated by basement shortening on folds and/or faults (BURKHARD, 1990) associated with the last stages of continent-continent collision. BURKHARD (1990) concluded that its root zone was already backfolded and steepened before 15 Ma (i.e., mid-Miocene) because there is no discontinuity in the apatite ages across the present day structure. However, the faster, younger, late Miocene to Recent exhumation of the eastern Aar massif and overlying nappes could reflect lateral variations in the isostatic response to continued tectonic thickening of the European crust. Alternatively, erosion of material following tectonism and mountain building may have induced passive isostatic rebound of the crust. The maximum present local (geodetic) surface uplift rate in the region, of 1.4 mm/yr, is centred around Chur (JEANRICHARD, 1975; SCHAER et al., 1975). The increase in the Miocene-Pliocene exhumation rates in this direction, documented above, may indicate that a Pliocene local surface uplift maximum centred around Chur continues to the present day. This hypothesis supports the conclusion of FLISCH (1986, in MICHALSKI and SOOM, 1990) that the beginning of the Chur uplift was around 3 Ma.

7. Conclusions

Fission-track age determinations on zircons and apatites from a series of samples from the Infrahelvetic Sardona unit of eastern Switzerland provide new information about the exhumation pattern of the eastern Aar massif and the overlying Glarus nappes:

(a) Zircon ages are mixed Variscan and Alpine ages, exhibiting a modal age of 160 Ma. Partial annealing of the tracks, despite peak paleotemperatures of around 300 °C, may be explicable by the short effective heating time for the peak metamorphism of only 1 Myr.

(b) Apatite cooling ages from the Sardona unit of 3.5 ± 0.1 Ma and 4.5 ± 0.4 Ma (i.e., late Miocene-Pliocene) suggest that there was an eastward younging in the onset of exhumation of material between the eastern Aar massif and Calfeisental.

(c) Apatite ages show better correspondence between age and perpendicular distance from the Glarus Overthrust than between age and elevation above mean sea level, suggesting that arching of the Glarus Overthrust may be a very young feature.

(d) The calculated exhumation rate for the region Calfeisental-Pizol was 0.8 ± 0.2 mm/yr and may indicate that there was a Pliocene surface uplift maximum centred around Chur that continues to the present day.

(e) At least 3500 m of denudation can be accounted for since the early Miocene, suggesting that erosional surface processes are the principal cause for the Miocene-Recent regional exhumation of material.

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