

## DR2003115

### GSA data repository

#### *Apatite (U-Th)/He analysis*

During sampling, the first 10cm of rock was removed to avoid possible He loss due to insolation or forest fires (Wolf et al., 1996). Apatite grains for each of the samples were prepared following a similar procedure as described in House *et. al.* (2000). Since it has recently become clear that the grain size is the diffusion domain for helium diffusion in apatite (Farley, 2000), single to few-grain samples were selected. In the case of multiple grain samples, the standard deviation of the average grain diameter was < 5%. Diameter of the selected apatites ranges between 80-150  $\mu\text{m}$ . The grains were carefully handpicked under polarised light to check for inclusion-free grains. The apatite grains were placed in small inconell cups and heated to 950°C for 35 minutes in an inconell tube heated by an external oven. Each sample was re-heated at 950°C for 35 minutes to check on complete He extraction, however no additional He was detected in the samples. He abundances were determined on a VG5400 mass spectrometer after a standard clean-up procedure (van Soest et al., 1998). For the He-determinations peak height comparison was used. The response of the VG5400 used in Amsterdam is linear over the He-pressure range encountered during the analysis of the samples. This is also demonstrated by the reproducible ages of the various splits of Durango apatites, covering a He-pressure range (He-pressure is linearly dependent of the weight of the standard) of more than five orders of magnitudes (see Table DR1). He blanks during analysis were low, usually below detection limit ( $\sim 2.0 \times 10^{-12}$ ), occasionally up to  $\sim 6.0 \times 10^{-12}$ , and generally not significant ( $1\sigma$  errors of blank measurements exceeded 75%). Blank corrections were not performed, as changes on ages would be usually <1%.

Following He analysis, the grains were recovered from the cups and dissolved in a 1:1 mixture of concentrated  $\text{HNO}_3$  and HF in order to dissolve mineral inclusions (except zircon) that might have escaped handpicking. U and Th concentrations were measured on an HP4500Plus ICP-MS, without using a spike, by peak height comparison using bracketing of samples by standard solutions (BHVO-1; USGS basalt standard).

All He ages are corrected for  $\alpha$ -ejection (Ft correction, Farley, 2000), assuming a hexagonal geometry, following the procedures described by Farley (2002). Due to the grain-size of the analysed samples, in some cases the calculated Ft factor is smaller than reported in publications by other workers (e.g., House et al., 1999; Persano et al., 2002; Reiners et al., 2002; Wolf et al., 1997). Average error on (U-Th)/He age determinations, excluding Ft correction is  $\sim 5\%$  ( $2\sigma$ , based on reproducibility of ages of Durango standard, see below). The uncertainty of the Ft correction has been assessed by repeated length and diameter determinations of all samples and is usually in the order of 3-4%, occasionally up to 5-6%. The cumulative analytical and Ft correction uncertainty of is used and depicted in Figure 2 A.

To test the reproducibility of the standard, eight splits of Durango apatites (sieve fraction 160-180  $\mu\text{m}$ ) were analysed (Table DR1). Four Durango splits had weights of  $\sim 500$  mg ( $>100$  grains), while the other four Durango samples had weights ranging from 0.18-0.001 mg (10, 4 and two single grain samples, respectively). The mean He age of all eight Durango samples is  $32.6 \pm 1.7$  Ma ( $2\sigma$ ), which is in excellent agreement with published Durango apatite He ages ( $32.0 \pm 1$  Ma, Farley, 2002).

The Linear error weighted best fit of Figure 2 A. was calculated using TableCurve2D v.5.0.

### ***Apatite Fission Track analysis***

Apatite FT analyses were made at the Vrije Universiteit Amsterdam. Apatites were mounted, polished and etched for 20 seconds in 5 N  $\text{HNO}_3$  at  $21 \pm 1.5^\circ\text{C}$ . Mounts were covered with a low-U muscovite external detector and then irradiated for 14 hours at the 'low flux reactor' of the ECN at Petten (NL) with the CN5 dosimeter at  $1.56 \times 10^{15}$  neutrons/ $\text{cm}^2$ . After irradiation the micas were removed and etched in 48% HF for about 30 minutes. Sample ages were calculated using zeta calibration factors of  $334.5 \pm 6.6$  based on determinations from the Fish Canyon tuff standards. Samples were measured on an AxioPlan microscope using a 100x dry lens. Fission track ages were calculated using TrackKey (Dunkl, 2002). Thermal modeling on sample V-99-05 was carried out using AFTSolve (version 1.2.2., Ketcham et al., 2000), using the Laslett et al. (1987) annealing model. Sudden heating as observed in Figure 2 A. at 1-0.5 Ma is the result of the applied annealing model, however this artefact has no influence on the modelled temperature in the period of interest.

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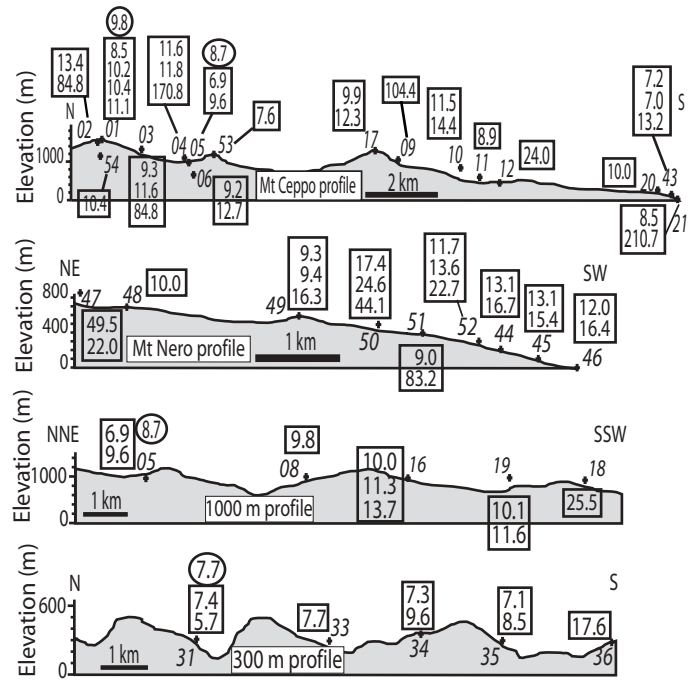
### GSA Data Repository figure captions

Table DR1. Sample details for (U-Th)/He analysis. He ages are corrected for  $\alpha$ -ejection after Farley (2002).

Table DR2. Fission track results.  $\rho_s$ = density of spontaneous tracks;  $\rho_i$ = density of induced tracks;  $\rho_d$ =density of tracks in the mica of the dosimeterglass.  $P(\chi^2)$  = probability of greater chi-squared; MTL = Mean Track Length. Central ages are given, calculated using Trackkey (Dunkl, 2002). Fission Track error is  $2\sigma$ .

Figure DR1. Ages plotted along four analysed profiles. Samples are labelled 'short' (e.g. 01, in stead of V-99-01). Boxes show  $\alpha$ -corrected (U-Th)/He ages, circles show fission-track (central) ages. He age errors are  $\sim 5\%$  ( $2\sigma$ , the analytical uncertainty of He-ages, excluding uncertainties of Ft corrections); Fission Track age errors are 15-20% ( $2\sigma$ ).

Data Repository Item



Foeken et al., Figure DR1

TABLE DR1. (U-Th)/He SAMPLE DETAILS

Sample	Elevation (m)	Coordinates (N)	Coordinates (E)	Rock description	Nr. grains	Weight (mg)	<sup>4</sup> He (μcm <sup>3</sup> STP/g)	U (ppm)	Th (ppm)	Uncorr. He age (Ma)	Ft	Corr. Age (Ma)
<b><u>Durango standards</u></b>												
Dur1	N.A.	N.A.	N.A.	N.A.	10	0.051	344	13	309	32.8	N.A.	N.A.
Dur2	N.A.	N.A.	N.A.	N.A.	30	0.18	327	12	279	34.6	N.A.	N.A.
Dur3	N.A.	N.A.	N.A.	N.A.	4	0.02	320	13	289	32.7	N.A.	N.A.
Dur4	N.A.	N.A.	N.A.	N.A.	1	0.001	1311	57	1117	33.6	N.A.	N.A.
Dur5	N.A.	N.A.	N.A.	N.A.	1	0.006	512	22	475	32.5	N.A.	N.A.
Dur6	N.A.	N.A.	N.A.	N.A.	>100	0.462	323	13	291	32.4	N.A.	N.A.
Dur9	N.A.	N.A.	N.A.	N.A.	>100	0.601	327	15	310	30.6	N.A.	N.A.
Dur10	N.A.	N.A.	N.A.	N.A.	>100	0.547	306	13	286	31.6	N.A.	N.A.
<b><u>Mte Ceppo vertical profile</u></b>												
V-99-01-I	1566	43 56'29"	007 45'35"	Cretaceous flysch	5	0.008	54	20	231	5.9	0.58	10.3
V-99-01-II	1566	43 56'29"	007 45'35"	Cretaceous flysch	3	0.01	30	11	133	5.9	0.57	10.5
V-99-01-III	1566	43 56'29"	007 45'35"	Cretaceous flysch	4	0.004	54	16	258	5.8	0.52	11.1
V-99-01-V	1566	43 56'29"	007 45'35"	Cretaceous flysch	4	0.008	50	21	234	5.3	0.63	8.5
V-99-02-I	1502	43 56'35"	007 45'56"	Cretaceous flysch	4	0.001	165	98	607	5.6	0.42	13.4
V-99-02-II	1502	43 56'35"	007 45'56"	Cretaceous flysch	2	0.001	below Helium detection level			N.D.	N.D.	N.D.
V-99-03-I	1306	43 55'54"	007 45'10"	Cretaceous flysch	3	0.009	294	16	115	56.3	0.66	84.8 *
V-99-03-II	1306	43 55'54"	007 45'10"	Cretaceous flysch	3	0.004	147	34	695	6.2	0.66	9.3
V-99-04-I	1115	43 55'05"	007 44'48"	Cretaceous flysch	3	0.001	186	104	712	5.7	0.49	11.6
V-99-04-II	1115	43 55'05"	007 44'48"	Cretaceous flysch	2	0.007	131	6	27	88.6	0.52	170.5 *
V-99-04-III	1115	43 55'05"	007 44'48"	Cretaceous flysch	4	0.009	54	39	64	8.3	0.70	11.8
V-99-05-I	921	43 55'03"	007 45'11"	Eocene flysch	2	0.003	78	32	508	4.3	0.62	6.9
V-99-05-II	921	43 55'03"	007 45'11"	Eocene flysch	1	0.002	below Helium detection level			N.D.	N.D.	N.D.
V-99-05-III	921	43 55'03"	007 45'11"	Eocene flysch	3	0.017	195	60	668	7.4	0.77	9.6
V-99-06-I	658	43 54'57"	007 46'29"	Eocene flysch	4	0.002	150	70	767	4.9	0.54	9.2
V-99-06-II	658	43 54'57"	007 46'29"	Eocene flysch	2	0.003	73	31	209	7.5	0.59	12.7
V-99-09-I	1042	43 51'59"	007 44'57"	Cretaceous flysch	2	0.002	failure during Helium analysis			N.D.	N.D.	N.D.
V-99-09-II	1042	43 51'59"	007 44'57"	Cretaceous flysch	2	0.004	41	4	4	66.5	0.64	104.4 §
V-99-10-I	829	43 51'12"	007 44'16"	Cretaceous flysch	2	0.002	66	42	171	6.6	0.46	14.3

Sample	Elevation (m)	Coordinates (N)	Coordinates (E)	Rock description	Nr. grains	Weight (mg)	4He ( $\mu\text{cm}^3\text{STP/g}$ )	U (ppm)	Th (ppm)	Uncorr. He age (Ma)	Ft	Corr. Age (Ma)
<b><u>Mte Ceppo vertical profile (continued)</u></b>												
V-99-10-II	829	43 51'12"	007 44'16"	Cretaceous flysch	2	0.005	63	12	297	6.3	0.55	11.5
V-99-11-I	591	43 50'48"	007 44'25"	Cretaceous flysch	1	0.014	26	8	101	6.7	0.74	9.0
V-99-11-II	591	43 50'48"	007 44'25"	Cretaceous flysch	1	0.001	below Helium detection level			N.D.	N.D.	N.D.
V-99-12-I	425	43 50'33"	007 44'49"	Cretaceous flysch	1	0.001	below Helium detection level			N.D.	N.D.	N.D.
V-99-12-II	425	43 50'33"	007 44'49"	Cretaceous flysch	1	0.002	37	11	49	13.4	0.56	24.0 <sup>§</sup>
V-99-17-I	1296	43 50'25"	007 44'00"	Cretaceous flysch	3	0.004	71	55	163	6.3	0.51	12.3
V-99-17-II	1296	43 50'25"	007 44'00"	Cretaceous flysch	2	0.011	60	45	95	7.2	0.73	9.9
V-99-20-I	265	43 48'03"	007 44'00"	Cretaceous flysch	6	0.003	59	34	252	5.2	0.38	13.4 <sup>#</sup>
V-99-20-II	265	43 48'03"	007 44'00"	Cretaceous flysch	4	0.002	78	73	182	5.5	0.55	10.0
V-99-21-I	5	43 47'42"	007 44'14"	Cretaceous flysch	4	0.003	142	64	826	4.5	0.53	8.5
V-99-21-II	5	43 47'42"	007 44'14"	Cretaceous flysch	4	0.001	122	1	25	139.3	0.66	210.9 <sup>*</sup>
V-99-43-I	115	398216	4850145	Cretaceous flysch	5	0.004	116	83	595	4.3	0.59	7.2
V-99-43-II	115	398216	4850145	Cretaceous flysch	4	0.002	137	84	753	4.3	0.61	7.0
V-99-43-III	115	398216	4850145	Cretaceous flysch	6	0.037	140	45	289	10.2	0.77	13.2 <sup>*</sup>
V-99-53-I	1233	no gps recording		Cretaceous flysch	4	0.005	113	51	698	4.3	0.57	7.6
V-99-53-II	1233	no gps recording		Cretaceous flysch	2	0.001	33	14	275	3.4	0.29	11.8 <sup>#</sup>
V-99-54-I	1150	43 56'10"	007 45'25"	Eocene flysch	1	0.003	10	8	30	5.4	0.52	10.4
V-99-54-II	1150	43 56'10"	007 45'25"	Eocene flysch	N.D.	N.D.	no duplicate measured		N.D.	N.D.	N.D.	N.D.
<b><u>1000m horizontal profile</u></b>												
V-99-05-I	921	43 55'03"	007 45'11"	Eocene flysch	2	0.003	78	32	508	4.3	0.62	6.9
V-99-05-II	921	43 55'03"	007 45'11"	Eocene flysch	1	0.002	below Helium detection level			N.D.	N.D.	N.D.
V-99-05-III	921	43 55'03"	007 45'11"	Eocene flysch	3	0.017	195	60	668	7.4	0.77	9.6
V-99-08-I	982	43 53'05"	007 44'09"	Cretaceous flysch	1	0.002	14	5	93	4.2	0.43	9.8
V-99-08-II	982	43 53'05"	007 44'09"	Cretaceous flysch	1	0.002	failure during Helium analysis			N.D.	N.D.	N.D.
V-99-16-I	966	43 52'02"	007 43'40"	Cretaceous flysch	3	0.003	142	53	408	7.8	0.57	13.7
V-99-16-II	966	43 52'02"	007 43'40"	Cretaceous flysch	3	0.004	71	27	306	5.9	0.59	10.0
V-99-16-III	966	43 52'02"	007 43'40"	Cretaceous flysch	5	0.006	194	80	567	7.5	0.66	11.3
V-99-18-I	904	43 49'55"	007 42'55"	Cretaceous flysch	3	0.005	failure during Helium analysis			N.D.	N.D.	N.D.
V-99-18-II	904	43 49'55"	007 42'55"	Cretaceous flysch	2	0.004	13	5	13	13.7	0.54	25.5 <sup>§</sup>
V-99-19-I	989	43 50'54"	007 42'40"	Cretaceous flysch	5	0.002	141	95	556	5.1	0.51	10.1

Sample	Elevation (m)	Coordinates (N)	Coordinates (E)	Rock description	Nr. grains	Weight (mg)	<sup>4</sup> He ( $\mu\text{cm}^3\text{STP/g}$ )	U (ppm)	Th (ppm)	Uncorr. He age (Ma)	Ft	Corr. Age (Ma)
<b><u>1000m horizontal profile (continued)</u></b>												
V-99-19-II	989	43 50'54"	007 42'40"	Cretaceous flysch	4	0.003	384	230	804	7.5	0.65	11.6
<b><u>300m horizontal profile</u></b>												
V-99-31-I	304	43 52'59"	007 40'19"	Eocene flysch	3	0.001	75	58	481	3.6	0.49	7.4
V-99-31-II	304	43 52'59"	007 40'19"	Eocene flysch	5	0.014	28	18	174	3.8	0.67	5.7
V-99-33-I	295	43 51'34"	007 39'51"	Eocene flysch	2	0.002	below Helium detection level			N.D.	N.D.	N.D.
V-99-33-II	295	43 51'34"	007 39'51"	Eocene flysch	3	0.001	84	70	423	4.1	0.53	7.7
V-99-34-I	356	43 50'28"	007 40'19"	Eocene flysch	3	0.004	115	54	609	4.8	0.66	7.3
V-99-34-II	356	43 50'28"	007 40'19"	Eocene flysch	2	0.001	121	90	377	5.6	0.58	9.6
V-99-35-I	292	43 49'32"	007 40'53"	Cretaceous flysch	3	0.002	37	47	87	4.5	0.53	8.5
V-99-35-II	292	43 49'32"	007 40'53"	Cretaceous flysch	3	0.002	48	47	264	3.6	0.51	7.1
V-99-36-I	288	43 48'14"	007 40'47"	Cretaceous flysch	4	0.002	164	116	25	11.0	0.63	17.6 <sup>§</sup>
V-99-36-II	288	43 48'14"	007 40'47"	Cretaceous flysch	3	0.003	failure during ICP-MS analysis			N.D.	N.D.	N.D.
<b><u>Mte Nero vertical profile</u></b>												
V-99-44-I	211	393564	4849849	Cretaceous flysch	3	0.006	93	42	215	8.3	0.63	13.1 **
V-99-44-II	211	393564	4849849	Cretaceous flysch	2	0.002	152	81	291	8.4	0.50	16.7 **
V-99-45-I	100	394373	4849352	Cretaceous flysch	9	0.008	199	99	349	9.0	0.59	15.4 **
V-99-45-II	100	394373	4849352	Cretaceous flysch	6	0.004	101	75	240	6.3	0.48	13.1 **
V-99-46-I	10	394023	4848908	Cretaceous flysch	7	0.005	243	142	537	7.5	0.62	12.0 **
V-99-46-II	10	394023	4848908	Cretaceous flysch	5	0.002	282	91	183	9.8	0.60	16.4 **
V-99-47-I	801	396654	4853849	Cretaceous flysch	3	0.002	159	34	38	30.2	0.61	49.5 **
V-99-47-II	801	396654	4853849	Cretaceous flysch	3	0.01	139	41	122	16.4	0.75	22.0 **
V-99-48-I	699	396088	4853336	Cretaceous flysch	1	0.001	334	354	183	6.9	0.69	10.0 **
V-99-49-I	600	394844	4851755	Cretaceous flysch	6	0.007	97	85	180	6.3	0.67	9.4 **
V-99-49-II	600	394844	4851755	Cretaceous flysch	6	0.004	38	17	91	8.1	0.50	16.3 **
V-99-49-III	600	394844	4851755	Cretaceous flysch	5	0.008	74	71	100	6.5	0.70	9.3 **
V-99-50-I	500	394402	4851170	Cretaceous flysch	3	0.003	268	69	20	30.0	0.68	44.1 **
V-99-50-II	500	394402	4851170	Cretaceous flysch	3	0.003	87	29	74	15.4	0.63	24.6 **
V-99-50-III	500	394402	4851170	Cretaceous flysch	4	0.041	93	51	13	14.1	0.81	17.4 **
V-99-51-I	406	394142	4850657	Cretaceous flysch	4	0.005	463	44	98	56.3	0.68	83.2 **



Sample	Altitude	Coordinates (N)	Coordinates (E)	Rock description	Nr. grains	Weight (mg)	4He ( $\mu\text{cm}^3\text{STP/g}$ )	U (ppm)	Th (ppm)	Uncorr. He age (Ma)	Ft	Corr. Age (Ma)
<b>Mte Nero vertical profile (continued)</b>												
V-99-51-II	406	394142	4850657	Cretaceous flysch	3	0.004	75	71	182	5.4	0.60	9.0 **
V-99-52-I	300	394055	4850338	Cretaceous flysch	1	0.001	152	55	344	9.2	0.68	16.3 **
V-99-52-II	300	394055	4850338	Cretaceous flysch	3	0.019	58	36	75	8.8	0.75	11.7 **
V-99-52-III	300	394055	4850338	Cretaceous flysch	5	0.119	154	54	49	19.2	0.85	22.7 **

\* He age not used in discussion because duplicate or triplicate measurements do not overlap within two standard deviations with the next younger age of the same sample. The higher age is then omitted.

§ In calculating the regression line, this data point lies outside the 99% prediction interval. It is therefore excluded from the calculated regression.

# Data point omitted from discussion because of very low Ft correction.

\*\* Mt Nero profile generally yielded poor reproducibility of duplicate or triplicate measurements, and are therefore omitted from the discussion.

TABLE DR2. FISSION TRACK SAMPLE DETAILS

Sample	Elevation	Nr of grains	$\rho_s \times 10^4 \text{ cm}^{-2}$	$\rho_i \times 10^5 \text{ cm}^{-2}$	$\rho_d \times 10^5 \text{ cm}^{-2}$	P( $\chi^2$ )	MTL $\mu\text{m}$ (nr of tracks)	Age (Ma)
V-99-01	1566	28	16.72 (205)	55.54 (3406)	90.88	0.8	13.0 (6)	10.3 $\pm$ 2.2
V-99-05	921	25	19.52 (391)	68.50 (6859)	90.88	0.0	13.7 (57)	8.7 $\pm$ 1.4
V-99-31	304	31	14.59 (259)	57.48 (5103)	90.88	4.7	12.4 (19)	7.7 $\pm$ 1.2