Preliminary results of 24 apatite fission track analyses of samples from four wells in the National Petroleum Reserve of Alaska, which are as follows:

Husky Oil NPR Operations Inc. Tunalik Test Well No. 1;
Husky Oil NPR Operations Inc. Walakpa Test Well No. 1;
Husky Oil NPR Operations Inc. Walakpa Test Well No. 2; and
Husky Oil NPR Operations Inc. Inigok Test Well No. 1.

APPENDIX A Fission track analysis: a summary of the technique and interpretation of results

From Paul O'Sullivan

APPENDIX B Apatite fission track analysis sample preparation

From Paul O'Sullivan

Received 14 August 1989

Total of 32 pages in report
Additional 32 pgs in Appendix A
Additional 8 pages in Appendix B

Geologic Materials Center Data Report No. 140

Preliminary Results of 24 Apatite Fission Track Analyses of Samples From Four Wells in the National Petroleum Reserve of Alaska.

Husky Tunalik Test Well #1
Husky Walapka Test Wells #1 and #2
Husky Inigok Test Well #1

by Paul B.O'Sullivan

Alaska Division of
Geological and Geophysical Surveys

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WELL LOCATION DATA

Tunalik Test Well #1 - located SW 1/4 of Section 20, T10N, R36W, Umiat Meridian

Walapka Test Well #1 - located SE 1/4 of Section 9, T20N, R19W, Umiat Meridian

Walapka Test Well #2 - located SW 1/4 of Section 30, T20N, R19W, Umiat Meridian

Inigok Test Well #1 - located NE 1/4 of Section 34, T8N, R5W, Umiat Meridian

INTRODUCTION

This is a preliminary report of apatite fission track analysis data of samples from four wells drilled in the National Petroleum Reserve of Alaska. During 1988, sandstone, siltstone, and conglomerate samples were collected from drill-core located at the State of Alaska's Geologic Materials Center in Eagle River. Apatite grains were separated from the samples and analyzed in Melbourne Australia at the LaTrobe University Fission Track Research Laboratory. All separations and analyses were completed by the author as part of an ongoing PhD project funded by the U.S. Minerals Management Service Continental Margins Program.

Each analysis includes two parts: 1) age report; and 2) track length distributions. The age report shows a listing of the individual grain ages, the resulting age and pertinent information used in determining the age. A guide to read the information is as follows:

POS 07A-KEMIK	-Sample number and unit collected
Irradiation:	-In-house number for grouping samples from the same irradiation package
Crystal	-Number of each grain counted
NS	-Number of spontaneous tracks counted
NI	-Number of induced tracks counted
NA	-Number of area units counted in grain
Ratio	-Ratio of (NS/NI) for each grain
U(ppm)	-Uranium concentration of each grain
RHOs	-Density of spontaneous tracks (per cm^2)
RHOi	-Density of induced tracks (per cm^2)
F.T.Age(Ma)	-Individual grain ages
CHI Squared	-Statistical test for determining multiple grain populations
p(chi squared)	-probability of less than 5% indicates multiple grain populations
Variance of SQR	-Statistical comparison of values of NS or NI for all grains
NS/NI	-Pooled ratio of (NS/NI). Uses total number of spontaneous and induced tracks counted for whole sample. Value used in age calculation if sample is of a single population
Mean Ratio	-Average ratio of (NS/NI) for grains
Pooled Age	-Age calculated using NS/NI(single population)
Mean Age	-Age calculated Using "Mean Ratio" (multiple populations)

The track length distributions for each sample are histograms showing the relative numbers of tracks measured at a particular length, the mean length of the tracks measured, the standard deviation of the tracks measured, and the total number of tracks measured for the sample (N).

LIST OF SAMPLES
(by depth)

Tunalik

Sample #	Unit	Depth (ft)	Results (data)
88 POS 100A	Echooka Fm.	16,946	Age only
88 POS 102A	Sag River SS.	15,418	Age and Length
88 POS 99A	Ivishak Fm.	14,852	Age and Length
88 POS 108A	Kingak Shale	11,692	Age and Length
88 POS 101A	Kingak Shale	10,932	Age and Length
88 POS 103A	Torok Fm.	9,501	Not Dateable
88 POS 104A	Torok Fm.	7,880	Not Dateable
88 POS 107A	Nanushuk Gp.	6,506	Age and Length
88 POS 106A	Nanushuk Gp.	5,558	Age and Length
88 POS 105A	Nanushuk Gp.	3,294	Age and Length

Walapka #1 and #2

Sample #	Unit	Depth (ft)	Results (data)
88 POS 112A	Pebble Shale	3,749	Age and Length
88 POS 111A	Pebble Shale	3,707	Combined w/ 112A
88 POS 115A	Argillite Basement	3,659	Age and Length
88 POS 114A	Barrow SS.	3,100	Age and Length
88 POS 110A	Pebble Shale	2,632	Age and Length
88 POS 113A	Pebble Shale	2,087	Age and Length
88 POS 109A	Torok Fm.	262	Age and Length

Inigok #1

Sample #	Unit	Depth (ft)	Results (data)
88 POS 116A	Kekiktuk Cong.	20,092	Not Dateable
88 POS 117A	Kekiktuk Cong.	19,369	Age Only
88 POS 118A	Echooka Fm.	13,832	Not Dateable
88 POS 119A	Fire Creek SS.	12,735	Age and Length
88 POS 120A	Fire Creek SS.	12,501	Age Only
88 POS 121A	Kingak Shale	10,296	Not Dateable
88 POS 122A	Kingak Shale	9,435	Age and Length
88 POS 123A	Torok Fm.	8,849	Age and Length
88 POS 124A	Torok Fm.	8,237	Age and Length
88 POS 125A	Torok Fm.	5,006	Age and Length
88 POS 126A	Nanushuk Gp.	3,078	Age and Length
88 POS 127A	Nanushuk Gp.	2,632	Age and Length

TUNALIK WELL
(in numerical order)

88 POS 99A - IVISHAK FM. - 14,852'

IRRADIATION LU021 SLIDE NUMBER 01
COUNTED BY: POS

No.	Ns	Ni	Na	RATIO	U(ppm)	RHOs	RHOi	F.T.AGE(Ma)
1	0	17	12	0.000	9.0	0.000E+00	1.656E+06	0.0± 0.0
2	0	14	12	0.000	7.4	0.000E+00	1.364E+06	0.0± 0.0
3	0	16	14	0.000	7.3	0.000E+00	1.336E+06	0.0± 0.0
4	0	18	15	0.000	7.6	0.000E+00	1.403E+06	0.0± 0.0
5	2	16	6	0.125	17.0	3.896E+05	3.117E+06	53.0± 39.7
6	0	15	10	0.000	9.5	0.000E+00	1.753E+06	0.0± 0.0
7	1	14	15	0.071	5.9	7.792E+04	1.091E+06	30.3± 31.4
8	0	20	12	0.000	10.6	0.000E+00	1.948E+06	0.0± 0.0
9	0	18	12	0.000	9.5	0.000E+00	1.753E+06	0.0± 0.0
10	1	10	12	0.100	5.3	9.740E+04	9.740E+05	42.4± 44.5
11	0	20	15	0.000	8.5	0.000E+00	1.558E+06	0.0± 0.0
12	0	19	12	0.000	10.1	0.000E+00	1.851E+06	0.0± 0.0
13	2	24	15	0.083	10.2	1.558E+05	1.870E+06	35.4± 26.0
14	0	14	21	0.000	4.2	0.000E+00	7.792E+05	0.0± 0.0
15	0	16	12	0.000	8.5	0.000E+00	1.558E+06	0.0± 0.0
16	0	19	12	0.000	10.1	0.000E+00	1.851E+06	0.0± 0.0
17	1	17	15	0.059	7.2	7.792E+04	1.325E+06	25.0± 25.7
18	0	15	20	0.000	4.8	0.000E+00	8.766E+05	0.0± 0.0
	7	302			7.9	3.381E+04	1.459E+06	

Area of basic unit = 8.789E-07 cm-2

CHI SQUARED = 19.44956 WITH 17 DEGREES OF FREEDOM
P(chi squared) = 30.3 %
CORRELATION COEFFICIENT = 0.097
VARIANCE OF SQR(Ns) = .3007498
VARIANCE OF SQR(Ni) = .1459386

Ns/Ni = 0.023 ± 0.009
MEAN RATIO = 0.024 ± 0.010

POOLED AGE = 9.8 ± 3.8 Ma
MEAN AGE = 10.4 ± 4.2 Ma

Ages calculated using a zeta of 352.7 ± 3.9 for SRM612 glass
RHO D = 2.408E+06cm-2; ND = 11421

88 POS 100A - ECHOOKA FM. - 16,946'

IRRADIATION LU021 SLIDE NUMBER 02
COUNTED BY: POS

No.	Ns	Ni	Na	RATIO	U(ppm)	RHOs	RHOi	F.T.AGE(Ma)
1	0	16	12	0.000	8.5	0.000E+00	1.558E+06	0.0± 0.0
2	1	15	36	0.067	2.6	3.247E+04	4.870E+05	28.3± 29.2
3	0	10	6	0.000	10.6	0.000E+00	1.948E+06	0.0± 0.0
4	0	18	14	0.000	8.2	0.000E+00	1.503E+06	0.0± 0.0
5	2	33	6	0.061	35.0	3.896E+05	6.428E+06	25.7± 18.8
6	0	50	12	0.000	26.5	0.000E+00	4.870E+06	0.0± 0.0
7	1	9	14	0.111	4.1	8.348E+04	7.514E+05	47.1± 49.7
8	0	23	16	0.000	9.1	0.000E+00	1.680E+06	0.0± 0.0
9	0	19	18	0.000	6.7	0.000E+00	1.234E+06	0.0± 0.0
10	0	31	20	0.000	9.9	0.000E+00	1.812E+06	0.0± 0.0
11	0	17	12	0.000	9.0	0.000E+00	1.656E+06	0.0± 0.0
12	0	8	6	0.000	8.5	0.000E+00	1.558E+06	0.0± 0.0
13	0	20	8	0.000	15.9	0.000E+00	2.922E+06	0.0± 0.0
14	0	31	16	0.000	12.3	0.000E+00	2.264E+06	0.0± 0.0
15	0	16	8	0.000	12.7	0.000E+00	2.338E+06	0.0± 0.0
	4	316			9.8	2.292E+04	1.810E+06	

Area of basic unit = 8.789E-07 cm-2

CHI SQUARED = 18.37251 WITH 14 DEGREES OF FREEDOM
P(chi squared) = 19.0 %
CORRELATION COEFFICIENT = 0.062
VARIANCE OF SQR(Ns) = .2302054
VARIANCE OF SQR(Ni) = 1.317921

Ns/Ni = 0.013 ± 0.006
MEAN RATIO = 0.016 ± 0.009

POOLED AGE = 5.5 ± 2.8 Ma
MEAN AGE = 6.9 ± 3.9 Ma

Ages calculated using a zeta of 352.7 ± 3.9 for SRM612 glass
RHO D = 2.480E+06cm-2; ND = 11421

88 POS 101A - KINGAK SHALE - 10,932'

IRRADIATION LU021 SLIDE NUMBER 03
COUNTED BY: POS

No.	Ns	Ni	Na	RATIO	U(ppm)	RHOs	RHOi	F.T.AGE(Ma)
1	0	7	6	0.000	7.4	0.000E+00	1.364E+06	0.0± 0.0
2	1	34	15	0.029	14.4	7.792E+04	2.649E+06	12.5± 12.7
3	1	6	6	0.167	6.4	1.948E+05	1.169E+06	70.5± 76.2
4	0	12	12	0.000	6.4	0.000E+00	1.169E+06	0.0± 0.0
5	0	4	6	0.000	4.2	0.000E+00	7.792E+05	0.0± 0.0
6	1	9	9	0.111	6.4	1.299E+05	1.169E+06	47.1± 49.7
7	0	4	4	0.000	6.4	0.000E+00	1.169E+06	0.0± 0.0
8	2	13	12	0.154	6.9	1.948E+05	1.266E+06	65.1± 49.5
9	2	17	9	0.118	12.0	2.597E+05	2.208E+06	49.9± 37.3
10	0	9	6	0.000	9.5	0.000E+00	1.753E+06	0.0± 0.0
11	1	14	18	0.071	4.9	6.493E+04	9.090E+05	30.3± 31.4
12	0	7	8	0.000	5.6	0.000E+00	1.023E+06	0.0± 0.0
13	0	10	12	0.000	5.3	0.000E+00	9.740E+05	0.0± 0.0
14	1	7	8	0.143	5.6	1.461E+05	1.023E+06	60.5± 64.7
15	1	25	18	0.040	8.8	6.493E+04	1.623E+06	17.0± 17.3
16	0	5	6	0.000	5.3	0.000E+00	9.740E+05	0.0± 0.0
17	1	23	12	0.043	12.2	9.740E+04	2.240E+06	18.5± 18.9
18	1	6	8	0.167	4.8	1.461E+05	8.766E+05	70.5± 76.2
19	0	10	8	0.000	7.9	0.000E+00	1.461E+06	0.0± 0.0
20	1	15	10	0.067	9.5	1.169E+05	1.753E+06	28.3± 29.2
	13	237			7.8	7.873E+04	1.435E+06	

Area of basic unit = 8.789E-07 cm-2

CHI SQUARED = 11.1525 WITH 19 DEGREES OF FREEDOM
P(chi squared) = 91.9 %
CORRELATION COEFFICIENT = 0.451
VARIANCE OF SQR(Ns) = .3160219
VARIANCE OF SQR(Ni) = 1.069143

Ns/Ni = 0.055 ± 0.016
MEAN RATIO = 0.055 ± 0.014

POOLED AGE = 24.2 ± 6.9 Ma
MEAN AGE = 24.5 ± 6.3 Ma

Ages calculated using a zeta of 352.7 ± 3.9 for SRM612 glass
RHO D = 2.507E+06cm-2; ND = 11421

88 POS 102A - SAG RIVER SS. - 15,418'

IRRADIATION LU021 SLIDE NUMBER 4
COUNTED BY: POS

No.	Ns	Ni	Na	RATIO	U(ppm)	RHOs	RHOi	F.T.AGE(Ma)
1	0	16	12	0.000	8.5	0.000E+00	1.558E+06	0.0± 0.0
2	1	15	6	0.067	15.9	1.948E+05	2.922E+06	28.3± 29.2
3	0	9	6	0.000	9.5	0.000E+00	1.753E+06	0.0± 0.0
4	0	19	8	0.000	15.1	0.000E+00	2.776E+06	0.0± 0.0
5	0	24	10	0.000	15.3	0.000E+00	2.805E+06	0.0± 0.0
6	1	10	6	0.100	10.6	1.948E+05	1.948E+06	42.4± 44.5
7	0	18	8	0.000	14.3	0.000E+00	2.630E+06	0.0± 0.0
8	0	19	12	0.000	10.1	0.000E+00	1.851E+06	0.0± 0.0
9	0	17	6	0.000	18.0	0.000E+00	3.312E+06	0.0± 0.0
10	0	14	8	0.000	11.1	0.000E+00	2.045E+06	0.0± 0.0
11	0	16	12	0.000	8.5	0.000E+00	1.558E+06	0.0± 0.0
12	1	15	12	0.067	7.9	9.740E+04	1.461E+06	28.3± 29.2
13	1	23	6	0.043	24.4	1.948E+05	4.480E+06	18.5± 18.9
	4	215			12.2	4.174E+04	2.244E+06	

Area of basic unit = 8.789E-07 cm-2

CHI SQUARED = 10.29022 WITH 12 DEGREES OF FREEDOM
P(chi squared) = 59.1 %
CORRELATION COEFFICIENT = -0.127
VARIANCE OF SQR(Ns) = .2307692
VARIANCE OF SQR(Ni) = .2966563

Ns/Ni = 0.019 ± 0.009
MEAN RATIO = 0.021 ± 0.010

POOLED AGE = 8.3 ± 4.2 Ma
MEAN AGE = 9.5 ± 4.4 Ma

Ages calculated using a zeta of 352.7 ± 3.9 for SRM612 glass
RHO D = 2.534E+06cm-2; ND = 11421

88 POS 105A - NANUSHUK GROUP - 3,294'

IRRADIATION LU021 SLIDE NUMBER 06
COUNTED BY: POS

No.	Ns	Ni	Na	RATIO	U(ppm)	RHOs	RHOi	F.T.AGE(Ma)
1	11	28	28	0.393	6.4	4.592E+05	1.169E+06	165.1± 58.8
2	7	46	15	0.152	19.5	5.454E+05	3.584E+06	64.4± 26.2
3	1	5	12	0.200	2.6	9.740E+04	4.870E+05	84.6± 92.6
4	5	31	40	0.161	4.9	1.461E+05	9.058E+05	68.3± 32.9
5	25	147	36	0.170	26.0	8.116E+05	4.772E+06	72.0± 15.6
6	1	12	9	0.083	8.5	1.299E+05	1.558E+06	35.4± 36.8
7	5	11	18	0.455	3.9	3.247E+05	7.142E+05	190.6±102.8
8	26	129	18	0.202	45.6	1.688E+06	8.376E+06	85.2± 18.4
9	9	66	15	0.136	28.0	7.013E+05	5.143E+06	57.8± 20.5
10	1	20	10	0.050	12.7	1.169E+05	2.338E+06	21.2± 21.8
11	5	31	20	0.161	9.9	2.922E+05	1.812E+06	68.3± 32.9
12	7	57	12	0.123	30.2	6.818E+05	5.552E+06	52.1± 20.9
13	3	13	12	0.231	6.9	2.922E+05	1.266E+06	97.5± 62.5
14	6	35	30	0.171	7.4	2.338E+05	1.364E+06	72.6± 32.1
15	11	42	24	0.262	11.1	5.357E+05	2.045E+06	110.5± 37.5
16	5	32	24	0.156	8.5	2.435E+05	1.558E+06	66.2± 31.8
17	7	45	30	0.156	9.5	2.727E+05	1.753E+06	65.9± 26.8
18	9	61	12	0.148	32.3	8.766E+05	5.941E+06	62.5± 22.3
19	1	17	12	0.059	9.0	9.740E+04	1.656E+06	25.0± 25.7
20	26	138	15	0.188	58.5	2.026E+06	1.075E+07	79.7± 17.1
	171	966			15.7	5.098E+05	2.880E+06	

Area of basic unit = 8.789E-07 cm-2

CHI SQUARED = 16.1911 WITH 19 DEGREES OF FREEDOM
P(chi squared) = 64.4 %
CORRELATION COEFFICIENT = 0.955
VARIANCE OF SQR(Ns) = 1.637335
VARIANCE OF SQR(Ni) = 7.792015

Ns/Ni = 0.177 ± 0.015
MEAN RATIO = 0.183 ± 0.022

POOLED AGE = 80.3 ± 6.7 Ma
MEAN AGE = 82.9 ± 9.9 Ma

Ages calculated using a zeta of 352.7 ± 3.9 for SRM612 glass
RHO D = 2.588E+06cm-2; ND = 11421

88 POS 106A - NANUSHUK GROUP - 5,558'

IRRADIATION LU021 SLIDE NUMBER 07
COUNTED BY: POS

No.	Ns	Ni	Na	RATIO	U(ppm)	RHOs	RHOi	F.T.AGE(Ma)
1	3	19	28	0.158	4.3	1.252E+05	7.931E+05	66.9± 41.5
2	3	14	21	0.214	4.2	1.670E+05	7.792E+05	90.6± 57.6
3	4	20	20	0.200	6.4	2.338E+05	1.169E+06	84.6± 46.3
4	3	17	10	0.176	10.8	3.506E+05	1.987E+06	74.7± 46.8
5	6	37	12	0.162	19.6	5.844E+05	3.604E+06	68.7± 30.2
6	1	7	12	0.143	3.7	9.740E+04	6.818E+05	60.5± 64.7
7	5	58	21	0.086	17.6	2.783E+05	3.228E+06	36.6± 17.1
8	3	9	10	0.333	5.7	3.506E+05	1.052E+06	140.3± 93.6
9	1	8	12	0.125	4.2	9.740E+04	7.792E+05	53.0± 56.2
10	1	9	12	0.111	4.8	9.740E+04	8.766E+05	47.1± 49.7
11	5	58	18	0.086	20.5	3.247E+05	3.766E+06	36.6± 17.1
12	0	3	9	0.000	2.1	0.000E+00	3.896E+05	0.0± 0.0
13	1	13	15	0.077	5.5	7.792E+04	1.013E+06	32.7± 33.9
14	2	21	12	0.095	11.1	1.948E+05	2.045E+06	40.4± 29.9
15	2	12	16	0.167	4.8	1.461E+05	8.766E+05	70.5± 53.9
16	3	19	12	0.158	10.1	2.922E+05	1.851E+06	66.9± 41.5
17	4	21	20	0.190	6.7	2.338E+05	1.227E+06	80.6± 44.0
18	1	8	12	0.125	4.2	9.740E+04	7.792E+05	53.0± 56.2
19	5	41	15	0.122	17.4	3.896E+05	3.195E+06	51.7± 24.5
20	2	17	12	0.118	9.0	1.948E+05	1.656E+06	49.9± 37.3
	55	411			8.7	2.150E+05	1.607E+06	

Area of basic unit = 8.789E-07 cm-2

CHI SQUARED = 6.974223 WITH 19 DEGREES OF FREEDOM
P(chi squared) = 99.4 %
CORRELATION COEFFICIENT = 0.829
VARIANCE OF SQR(Ns) = .3558942
VARIANCE OF SQR(Ni) = 2.544674

Ns/Ni = 0.134 ± 0.019
MEAN RATIO = 0.142 ± 0.015

POOLED AGE = 61.4 ± 8.8 Ma
MEAN AGE = 65.3 ± 6.9 Ma

Ages calculated using a zeta of 352.7 ± 3.9 for SRM612 glass
RHO D = 2.616E+06cm-2; ND = 11421

88 POS 107A - TOROK FM. - 6,506'

IRRADIATION LU021 SLIDE NUMBER 08
COUNTED BY: POS

No.	Ns	Ni	Na	RATIO	U(ppm)	RHOs	RHOi	F.T.AGE(Ma)
1	0	11	30	0.000	2.3	0.000E+00	4.285E+05	0.0± 0.0
2	1	6	24	0.167	1.6	4.870E+04	2.922E+05	70.5± 76.2
3	3	18	12	0.167	9.5	2.922E+05	1.753E+06	70.5± 44.0
4	28	280	28	0.100	63.6	1.169E+06	1.169E+07	42.4± 8.4
5	4	24	8	0.167	19.1	5.844E+05	3.506E+06	70.5± 38.1
6	3	23	15	0.130	9.7	2.338E+05	1.792E+06	55.3± 33.9
7	1	7	12	0.143	3.7	9.740E+04	6.818E+05	60.5± 64.7
8	1	10	10	0.100	6.4	1.169E+05	1.169E+06	42.4± 44.5
9	8	49	24	0.163	13.0	3.896E+05	2.386E+06	69.1± 26.4
10	11	77	18	0.143	27.2	7.142E+05	5.000E+06	60.5± 19.5
11	5	17	10	0.294	10.8	5.844E+05	1.987E+06	124.0± 63.1
12	3	22	8	0.136	17.5	4.383E+05	3.214E+06	57.8± 35.6
13	1	10	28	0.100	2.3	4.174E+04	4.174E+05	42.4± 44.5
14	3	19	12	0.158	10.1	2.922E+05	1.851E+06	66.9± 41.5
15	4	23	10	0.174	14.6	4.675E+05	2.688E+06	73.6± 39.9
16	1	8	10	0.125	5.1	1.169E+05	9.350E+05	53.0± 56.2
17	8	50	24	0.160	13.2	3.896E+05	2.435E+06	67.7± 25.8
18	5	27	12	0.185	14.3	4.870E+05	2.630E+06	78.3± 38.2
19	12	85	15	0.141	36.0	9.350E+05	6.623E+06	59.8± 18.5
20	1	10	10	0.100	6.4	1.169E+05	1.169E+06	42.4± 44.5
	103	776			15.4	3.762E+05	2.834E+06	

Area of basic unit = 8.789E-07 cm-2

CHI SQUARED = 8.110324 WITH 19 DEGREES OF FREEDOM
P(chi squared) = 98.6 %
CORRELATION COEFFICIENT = 0.976
VARIANCE OF SQR(Ns) = 1.391811
VARIANCE OF SQR(Ni) = 10.92243

Ns/Ni = 0.133 ± 0.014
MEAN RATIO = 0.143 ± 0.012

POOLED AGE = 61.8 ± 6.5 Ma
MEAN AGE = 66.4 ± 5.7 Ma

Ages calculated using a zeta of 352.7 ± 3.9 for SRM612 glass
RHO D = 2.653E+06cm-2; ND = 11421

88 POS 108A - KINGAK SHALE - 11,692

IRRADIATION LU021 SLIDE NUMBER 09
COUNTED BY: POS

No.	Ns	Ni	Na	RATIO	U(ppm)	RHOs	RHOi	F.T.AGE(Ma)
1	6	44	40	0.136	7.0	1.753E+05	1.286E+06	57.8± 25.2
2	1	25	12	0.040	13.2	9.740E+04	2.435E+06	17.0± 17.3
3	0	25	15	0.000	10.6	0.000E+00	1.948E+06	0.0± 0.0
4	1	15	12	0.067	7.9	9.740E+04	1.461E+06	28.3± 29.2
5	0	19	15	0.000	8.1	0.000E+00	1.480E+06	0.0± 0.0
6	0	7	6	0.000	7.4	0.000E+00	1.364E+06	0.0± 0.0
7	1	30	15	0.033	12.7	7.792E+04	2.338E+06	14.2± 14.4
8	0	12	8	0.000	9.5	0.000E+00	1.753E+06	0.0± 0.0
9	2	19	12	0.105	10.1	1.948E+05	1.851E+06	44.6± 33.2
10	1	25	15	0.040	10.6	7.792E+04	1.948E+06	17.0± 17.3
11	1	12	10	0.083	7.6	1.169E+05	1.403E+06	35.4± 36.8
12	1	8	12	0.125	4.2	9.740E+04	7.792E+05	53.0± 56.2
13	0	15	10	0.000	9.5	0.000E+00	1.753E+06	0.0± 0.0
	14	256			8.9	8.991E+04	1.644E+06	

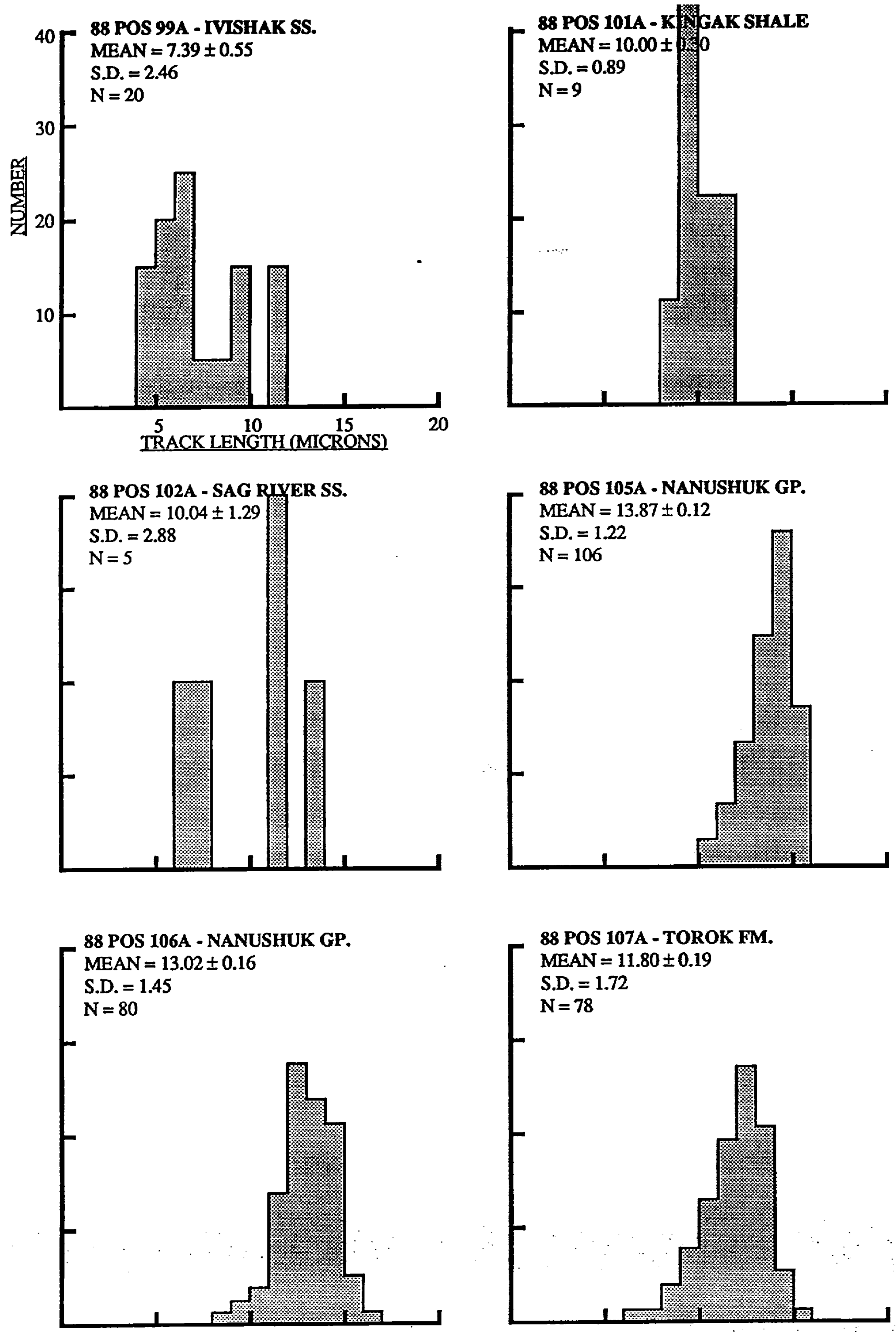
Area of basic unit = 8.789E-07 cm-2

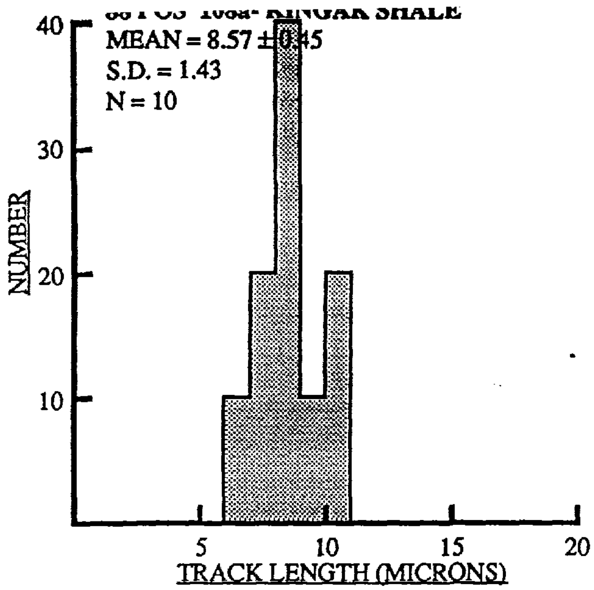
CHI SQUARED = 11.07058 WITH 12 DEGREES OF FREEDOM
P(chi squared) = 52.3 %
CORRELATION COEFFICIENT = 0.721
VARIANCE OF SQR(Ns) = .5429959
VARIANCE OF SQR(Ni) = 1.247556

Ns/Ni = 0.055 ± 0.015
MEAN RATIO = 0.048 ± 0.014

POOLED AGE = 25.8 ± 7.1 Ma
MEAN AGE = 22.9 ± 6.6 Ma

Ages calculated using a zeta of 352.7 ± 3.9 for SRM612 glass
RHO D = 2.680E+06cm-2; ND = 11421


88 POS 99A - IVISHAK SS.
MEAN = 7.39 ± 0.55
S.D. = 2.46
N = 20
NUMBER
40
30
20
10
5
10
15
20
TRACK LENGTH (MICRONS)
88 POS 101A - KINGAK SHALE
MEAN = 10.00 ± 0.30
S.D. = 0.89
N = 9
88 POS 102A - SAG RIVER SS.
MEAN = 10.04 ± 1.29
S.D. = 2.88
N = 5
88 POS 105A - NANUSHUK GP.
MEAN = 13.87 ± 0.12
S.D. = 1.22
N = 106
88 POS 106A - NANUSHUK GP.
MEAN = 13.02 ± 0.16
S.D. = 1.45
N = 80
88 POS 107A - TOROK FM.
MEAN = 11.80 ± 0.19
S.D. = 1.72
N = 78


MEAN = 8.57 ± 0.45
S.D. = 1.43
N = 10
NUMBER
TRACK LENGTH (MICRONS)

Walapka #1, #2
(in numerical order)

88 POS 109A - TOROK FM. - 262' - WALAPKA #1

IRRADIATION LU021 SLIDE NUMBER 10
COUNTED BY: POS

No.	Ns	Ni	Na	RATIO	U(ppm)	RHOs	RHOi	F.T.AGE(Ma)
1	6	14	12	0.429	7.4	5.844E+05	1.364E+06	179.9± 87.8
2	5	10	8	0.500	7.9	7.305E+05	1.461E+06	209.4±114.7
3	6	13	12	0.462	6.9	5.844E+05	1.266E+06	193.5± 95.5
4	5	36	15	0.139	15.3	3.896E+05	2.805E+06	58.8± 28.1
5	4	18	24	0.222	4.8	1.948E+05	8.766E+05	93.9± 51.9
6	12	22	12	0.545	11.7	1.169E+06	2.143E+06	228.1± 81.9
7	6	23	42	0.261	3.5	1.670E+05	6.400E+05	110.1± 50.5
8	16	52	25	0.308	13.2	7.480E+05	2.431E+06	129.6± 37.1
9	10	43	25	0.233	10.9	4.675E+05	2.010E+06	98.2± 34.5
10	8	18	8	0.444	14.3	1.169E+06	2.630E+06	186.4± 79.3
11	5	67	27	0.075	15.8	2.164E+05	2.900E+06	31.7± 14.7
12	4	10	18	0.400	3.5	2.597E+05	6.493E+05	168.0± 99.4
13	6	39	24	0.154	10.3	2.922E+05	1.899E+06	65.1± 28.6
14	10	29	32	0.345	5.8	3.652E+05	1.059E+06	145.1± 53.3
15	35	101	20	0.347	32.1	2.045E+06	5.902E+06	145.8± 28.7
16	4	8	15	0.500	3.4	3.117E+05	6.233E+05	209.4±128.2
17	2	8	16	0.250	3.2	1.461E+05	5.844E+05	105.5± 83.4
18	6	15	14	0.400	6.8	5.009E+05	1.252E+06	168.0± 81.2
19	6	14	12	0.429	7.4	5.844E+05	1.364E+06	179.9± 87.8
20	4	18	20	0.222	5.7	2.338E+05	1.052E+06	93.9± 51.9
	160	558			9.3	4.908E+05	1.712E+06	

Area of basic unit = 8.789E-07 cm-2

CHI SQUARED = 25.81069 WITH 19 DEGREES OF FREEDOM
P(chi squared) = 13.6 %
CORRELATION COEFFICIENT = 0.798
VARIANCE OF SQR(Ns) = .9302874
VARIANCE OF SQR(Ni) = 3.684916

Ns/Ni = 0.287 ± 0.026
MEAN RATIO = 0.333 ± 0.030

POOLED AGE = 135.5 ± 12.2 Ma
MEAN AGE = 157.1 ± 14.2 Ma

Ages calculated using a zeta of 352.7 ± 3.9 for SRM612 glass
RHO D = 2.707E+06cm-2; ND = 11421

88 POS 110A - - 2,632' - WALAPKA #2

IRRADIATION LU021 SLIDE NUMBER 11
COUNTED BY: POS

No.	Ns	Ni	Na	RATIO	U(ppm)	RHOs	RHOi	F.T.AGE(Ma)
1	3	30	25	0.100	7.6	1.403E+05	1.403E+06	42.4± 25.7
2	7	58	21	0.121	17.6	3.896E+05	3.228E+06	51.2± 20.5
3	8	41	25	0.195	10.4	3.740E+05	1.917E+06	82.5± 31.9
4	8	24	25	0.333	6.1	3.740E+05	1.122E+06	140.3± 57.3
5	1	11	40	0.091	1.7	2.922E+04	3.214E+05	38.6± 40.3
6	13	60	42	0.217	9.1	3.618E+05	1.670E+06	91.6± 28.0
7	8	48	21	0.167	14.5	4.452E+05	2.671E+06	70.5± 27.0
8	35	113	30	0.310	23.9	1.364E+06	4.402E+06	130.5± 25.3
9	18	21	24	0.857	5.6	8.766E+05	1.023E+06	354.9±114.1
10	3	13	30	0.231	2.8	1.169E+05	5.065E+05	97.5± 62.5
11	10	16	16	0.625	6.4	7.305E+05	1.169E+06	260.7±105.1
12	35	176	40	0.199	28.0	1.023E+06	5.143E+06	84.1± 15.6
13	4	24	24	0.167	6.4	1.948E+05	1.169E+06	70.5± 38.1
14	3	30	25	0.100	7.6	1.403E+05	1.403E+06	42.4± 25.7
15	7	45	24	0.156	11.9	3.409E+05	2.191E+06	65.9± 26.8
16	2	9	40	0.222	1.4	5.844E+04	2.630E+05	93.9± 73.4
17	9	50	21	0.180	15.1	5.009E+05	2.783E+06	76.2± 27.6
18	20	25	24	0.800	6.6	9.740E+05	1.217E+06	331.8± 99.7
19	9	15	16	0.600	6.0	6.574E+05	1.096E+06	250.4±105.7
20	4	21	24	0.190	5.6	1.948E+05	1.023E+06	80.6± 44.0
	207	830			9.8	4.505E+05	1.806E+06	

Area of basic unit = 8.789E-07 cm-2

CHI SQUARED = 61.21191 WITH 19 DEGREES OF FREEDOM
P(chi squared) = 0.0 %
CORRELATION COEFFICIENT = 0.809
VARIANCE OF SQR(Ns) = 1.826539
VARIANCE OF SQR(Ni) = 6.367232

Ns/Ni = 0.249 ± 0.019
MEAN RATIO = 0.293 ± 0.052

POOLED AGE = 119.2 ± 9.3 Ma
MEAN AGE = 139.8 ± 24.9 Ma

Ages calculated using a zeta of 352.7 ± 3.9 for SRM612 glass
RHO D = 2.735E+06cm-2; ND = 11421

88 POS 111A + 112A - - 3,707'+3,749' - WALAPKA #2

IRRADIATION LU021 SLIDE NUMBER 13
COUNTED BY: POS

No.	Ns	Ni	Na	RATIO	U(ppm)	RHOs	RHOi	F.T.AGE(Ma)
1	16	49	21	0.327	14.8	8.905E+05	2.727E+06	137.5± 39.6
2	23	114	25	0.202	29.0	1.075E+06	5.330E+06	85.3± 19.5
3	3	22	15	0.136	9.3	2.338E+05	1.714E+06	57.8± 35.6
4	4	11	20	0.364	3.5	2.338E+05	6.428E+05	152.9± 89.3
5	8	28	10	0.286	17.8	9.350E+05	3.273E+06	120.5± 48.3
6	8	49	48	0.163	6.5	1.948E+05	1.193E+06	69.1± 26.4
7	9	23	40	0.391	3.7	2.630E+05	6.720E+05	164.4± 64.7
8	14	83	30	0.169	17.6	5.454E+05	3.234E+06	71.4± 20.7
9	17	60	24	0.283	15.9	8.279E+05	2.922E+06	119.5± 32.9
10	10	70	14	0.143	31.8	8.348E+05	5.844E+06	60.5± 20.5
11	2	9	12	0.222	4.8	1.948E+05	8.766E+05	93.9± 73.4
12	15	48	20	0.312	15.3	8.766E+05	2.805E+06	131.6± 39.0
13	10	41	30	0.244	8.7	3.896E+05	1.597E+06	103.0± 36.4
14	19	61	25	0.311	15.5	8.883E+05	2.852E+06	131.2± 34.5
15	8	26	18	0.308	9.2	5.195E+05	1.688E+06	129.6± 52.4
16	3	12	6	0.250	12.7	5.844E+05	2.338E+06	105.5± 68.1
17	27	81	40	0.333	12.9	7.889E+05	2.367E+06	140.3± 31.2
18	9	21	30	0.429	4.4	3.506E+05	8.181E+05	179.9± 71.7
19	17	51	20	0.333	16.2	9.935E+05	2.980E+06	140.3± 39.4
20	8	38	12	0.211	20.1	7.792E+05	3.701E+06	89.0± 34.6
	230	897			12.4	5.844E+05	2.279E+06	

Area of basic unit = 8.789E-07 cm-2

CHI SQUARED = 16.77851 WITH 19 DEGREES OF FREEDOM
P(chi squared) = 60.5 %
CORRELATION COEFFICIENT = 0.838
VARIANCE OF SQR(Ns) = 1.079595
VARIANCE OF SQR(Ni) = 4.372144

Ns/Ni = 0.256 ± 0.019
MEAN RATIO = 0.271 ± 0.019

POOLED AGE = 124.6 ± 9.3 Ma
MEAN AGE = 131.5 ± 9.1 Ma

Ages calculated using a zeta of 352.7 ± 3.9 for SRM612 glass
RHO D = 2.782E+06cm-2; ND = 11421

88 POS 113A - - 2,087' - WALAPKA #1

IRRADIATION LU021 SLIDE NUMBER 14
COUNTED BY: POS

No.	Ns	Ni	Na	RATIO	U(ppm)	RHOs	RHOi	F.T.AGE(Ma)
1	5	15	12	0.333	7.9	4.870E+05	1.461E+06	140.3± 72.5
2	2	7	12	0.286	3.7	1.948E+05	6.818E+05	120.5± 96.6
3	4	10	12	0.400	5.3	3.896E+05	9.740E+05	168.0± 99.4
4	2	8	10	0.250	5.1	2.338E+05	9.350E+05	105.5± 83.4
5	45	180	18	0.250	63.6	2.922E+06	1.169E+07	105.5± 17.7
6	6	19	8	0.316	15.1	8.766E+05	2.776E+06	133.0± 62.3
7	3	6	12	0.500	3.2	2.922E+05	5.844E+05	209.4±148.1
8	1	4	4	0.250	6.4	2.922E+05	1.169E+06	105.5±118.0
9	2	7	12	0.286	3.7	1.948E+05	6.818E+05	120.5± 96.6
10	1	8	15	0.125	3.4	7.792E+04	6.233E+05	53.0± 56.2
11	1	5	9	0.200	3.5	1.299E+05	6.493E+05	84.6± 92.6
12	8	23	12	0.348	12.2	7.792E+05	2.240E+06	146.4± 60.1
13	23	109	16	0.211	43.3	1.680E+06	7.962E+06	89.2± 20.5
14	17	33	12	0.515	17.5	1.656E+06	3.214E+06	215.6± 64.4
15	7	22	24	0.318	5.8	3.409E+05	1.071E+06	134.0± 58.2
16	6	17	24	0.353	4.5	2.922E+05	8.279E+05	148.5± 70.5
17	6	18	24	0.333	4.8	2.922E+05	8.766E+05	140.3± 66.2
18	47	188	28	0.250	42.7	1.962E+06	7.847E+06	105.5± 17.3
19	9	28	20	0.321	8.9	5.259E+05	1.636E+06	135.4± 51.9
20	3	11	16	0.273	4.4	2.191E+05	8.035E+05	115.0± 75.0
	198	718			15.2	7.714E+05	2.797E+06	

Area of basic unit = 8.789E-07 cm-2

CHI SQUARED = 9.675831 WITH 19 DEGREES OF FREEDOM
P(chi squared) = 96.0 %
CORRELATION COEFFICIENT = 0.986
VARIANCE OF SQR(Ns) = 2.959536
VARIANCE OF SQR(Ni) = 12.10107

Ns/Ni = 0.276 ± 0.022
MEAN RATIO = 0.306 ± 0.021

POOLED AGE = 134.3 ± 10.9 Ma
MEAN AGE = 148.8 ± 10.2 Ma

Ages calculated using a zeta of 352.7 ± 3.9 for SRM612 glass
RHO D = 2.790E+06cm-2; ND = 11421

88 POS 114A - - 3,100' - WALAPKA #1

IRRADIATION LU023 SLIDE NUMBER 01
COUNTED BY: POS

No.	Ns	Ni	Na	RATIO	U(ppm)	RHOs	RHOi	F.T.AGE(Ma)
1	8	51	12	0.157	24.4	7.792E+05	4.967E+06	73.6± 28.0
2	16	51	21	0.314	13.9	8.905E+05	2.838E+06	146.3± 42.0
3	5	18	12	0.278	8.6	4.870E+05	1.753E+06	129.7± 65.6
4	8	28	15	0.286	10.7	6.233E+05	2.182E+06	133.4± 53.5
5	9	25	40	0.360	3.6	2.630E+05	7.305E+05	167.6± 65.2
6	17	59	24	0.288	14.1	8.279E+05	2.873E+06	134.5± 37.1
7	5	9	8	0.556	6.5	7.305E+05	1.315E+06	256.9±143.3
8	10	40	12	0.250	19.1	9.740E+05	3.896E+06	116.9± 41.4
9	8	22	20	0.364	6.3	4.675E+05	1.286E+06	169.3± 69.9
10	27	86	40	0.314	12.3	7.889E+05	2.513E+06	146.4± 32.4
11	17	62	30	0.274	11.9	6.623E+05	2.415E+06	128.1± 35.1
12	26	101	24	0.257	24.1	1.266E+06	4.919E+06	120.3± 26.5
13	5	11	20	0.455	3.2	2.922E+05	6.428E+05	210.9±113.8
14	8	50	40	0.160	7.2	2.338E+05	1.461E+06	75.0± 28.6
15	19	75	30	0.253	14.3	7.402E+05	2.922E+06	118.4± 30.5
16	17	50	40	0.340	7.2	4.967E+05	1.461E+06	158.4± 44.5
17	8	24	12	0.333	11.5	7.792E+05	2.338E+06	155.4± 63.5
	213	762			10.9	6.224E+05	2.226E+06	

Area of basic unit = 8.789E-07 cm-2

CHI SQUARED = 9.33778 WITH 16 DEGREES OF FREEDOM
P(chi squared) = 89.9 %
CORRELATION COEFFICIENT = 0.926
VARIANCE OF SQR(Ns) = .9294977
VARIANCE OF SQR(Ni) = 4.162098

Ns/Ni = 0.280 ± 0.022
MEAN RATIO = 0.308 ± 0.023

POOLED AGE = 121.8 ± 9.4 Ma
MEAN AGE = 133.2 ± 10.1 Ma

Ages calculated using a zeta of 352.7 ± 3.9 for SRM612 glass
RHO D = 2.477E+06cm-2; ND = 11864

88 POS 115A - ARGILLITE BASEMENT - 3,659' - WALAPKA #1

IRRADIATION LU023 SLIDE NUMBER 02
COUNTED BY: POS

No.	Ns	Ni	Na	RATIO	U(ppm)	RHOs	RHOi	F.T.AGE(Ma)
1	8	30	9	0.267	19.1	1.039E+06	3.896E+06	124.6± 49.6
2	5	14	18	0.357	4.5	3.247E+05	9.090E+05	166.3± 86.7
3	5	8	8	0.625	5.7	7.305E+05	1.169E+06	288.3±164.4
4	4	10	10	0.400	5.7	4.675E+05	1.169E+06	186.0±110.1
5	8	14	9	0.571	8.9	1.039E+06	1.818E+06	264.1±117.1
6	7	27	9	0.259	17.2	9.090E+05	3.506E+06	121.2± 51.4
7	9	24	8	0.375	17.2	1.315E+06	3.506E+06	174.5± 68.3
8	8	21	12	0.381	10.0	7.792E+05	2.045E+06	177.3± 73.7
9	10	52	16	0.192	18.6	7.305E+05	3.798E+06	90.1± 31.1
10	5	12	14	0.417	4.9	4.174E+05	1.002E+06	193.6±103.1
11	8	20	10	0.400	11.5	9.350E+05	2.338E+06	186.0± 77.8
12	17	45	20	0.378	12.9	9.935E+05	2.630E+06	175.8± 50.1
	94	277			11.1	7.683E+05	2.264E+06	

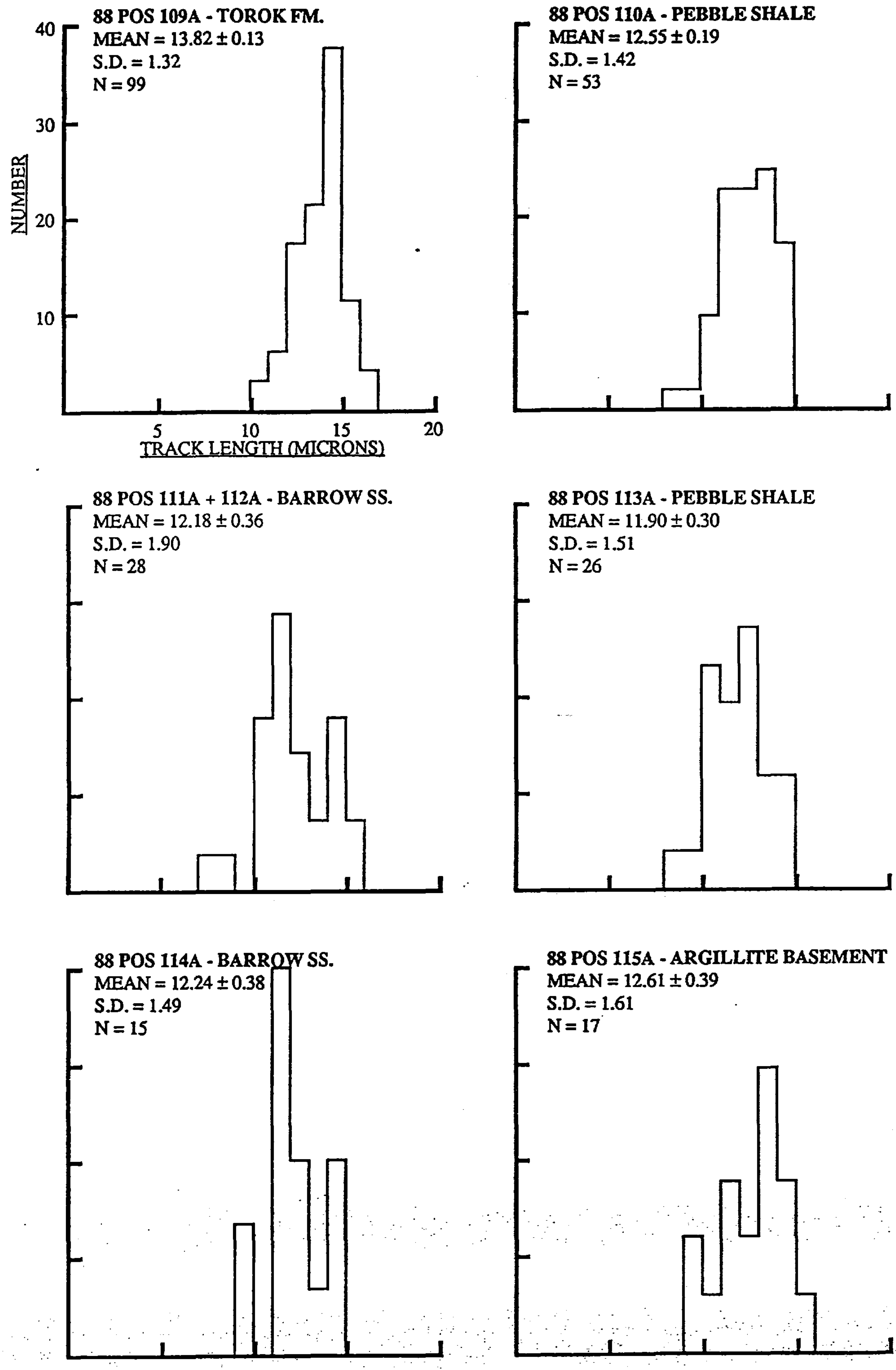
Area of basic unit = 8.789E-07 cm-2

CHI SQUARED = 6.826693 WITH 11 DEGREES OF FREEDOM
P(chi squared) = 81.3 %
CORRELATION COEFFICIENT = 0.790
VARIANCE OF SQR(Ns) = .3189163
VARIANCE OF SQR(Ni) = 1.859627

Ns/Ni = 0.339 ± 0.040
MEAN RATIO = 0.385 ± 0.035

POOLED AGE = 148.4 ± 17.8 Ma
MEAN AGE = 168.2 ± 15.4 Ma

Ages calculated using a zeta of 352.7 ± 3.9 for SRM612 glass
RHO D = 2.509E+06cm-2; ND = 11864



88 POS 109A - TOROK FM.
MEAN = 13.82 ± 0.13
S.D. = 1.32
N = 99
NUMBER
40
30
20
10
5
10
15
20
TRACK LENGTH (MICRONS)
88 POS 110A - PEBBLE SHALE
MEAN = 12.55 ± 0.19
S.D. = 1.42
N = 53
88 POS 111A + 112A - BARROW SS.
MEAN = 12.18 ± 0.36
S.D. = 1.90
N = 28
88 POS 113A - PEBBLE SHALE
MEAN = 11.90 ± 0.30
S.D. = 1.51
N = 26
88 POS 114A - BARROW SS.
MEAN = 12.24 ± 0.38
S.D. = 1.49
N = 15
88 POS 115A - ARGILLITE BASEMENT
MEAN = 12.61 ± 0.39
S.D. = 1.61
N = 17

INIGOK #1 WELL
(in numerical order)

88 POS 117A - KEKIKTUK CONG. - 19,369'

IRRADIATION LU023 SLIDE NUMBER 04
COUNTED BY: POS

No.	Ns	Ni	Na	RATIO	U(ppm)	RHOs	RHOi	F.T.AGE(Ma)
1	0	16	12	0.000	7.6	0.000E+00	1.558E+06	0.0± 0.0
2	0	15	30	0.000	2.9	0.000E+00	5.844E+05	0.0± 0.0
3	0	10	6	0.000	9.6	0.000E+00	1.948E+06	0.0± 0.0
4	0	18	14	0.000	7.4	0.000E+00	1.503E+06	0.0± 0.0
5	0	33	12	0.000	15.8	0.000E+00	3.214E+06	0.0± 0.0
6	1	50	12	0.020	23.9	9.740E+04	4.870E+06	9.4± 9.5
	1	142			9.5	1.359E+04	1.930E+06	

Area of basic unit = 8.789E-07 cm-2

CHI SQUARED = 1.816625 WITH 5 DEGREES OF FREEDOM
P(chi squared) = 87.4 %
CORRELATION COEFFICIENT = 0.857
VARIANCE OF SQR(Ns) = .1666667
VARIANCE OF SQR(Ni) = 2.091782

Ns/Ni = 0.007 ± 0.007
MEAN RATIO = 0.003 ± 0.003

POOLED AGE = 3.2 ± 3.2 Ma
MEAN AGE = 1.5 ± 1.5 Ma

Ages calculated using a zeta of 352.7 ± 3.9 for SRM612 glass
RHO D = 2.573E+06cm-2; ND = 11864

88 POS 119A - FIRE CREEK SS. - 12,735'

IRRADIATION LU023 SLIDE NUMBER 05
COUNTED BY: POS

No.	Ns	Ni	Na	RATIO	U(ppm)	RHOs	RHOi	F.T.AGE(Ma)
1	0	16	20	0.000	4.6	0.000E+00	9.350E+05	0.0± 0.0
2	1	10	9	0.100	6.4	1.299E+05	1.299E+06	47.0± 49.3
3	0	5	9	0.000	3.2	0.000E+00	6.493E+05	0.0± 0.0
4	0	10	12	0.000	4.8	0.000E+00	9.740E+05	0.0± 0.0
5	0	35	20	0.000	10.0	0.000E+00	2.045E+06	0.0± 0.0
6	2	31	12	0.065	14.8	1.948E+05	3.019E+06	30.4± 22.2
7	0	8	8	0.000	5.7	0.000E+00	1.169E+06	0.0± 0.0
8	1	20	12	0.050	9.6	9.740E+04	1.948E+06	23.5± 24.1
9	2	20	16	0.100	7.2	1.461E+05	1.461E+06	47.0± 34.9
10	0	16	12	0.000	7.6	0.000E+00	1.558E+06	0.0± 0.0
11	0	9	9	0.000	5.7	0.000E+00	1.169E+06	0.0± 0.0
12	0	15	16	0.000	5.4	0.000E+00	1.096E+06	0.0± 0.0
13	1	19	16	0.053	6.8	7.305E+04	1.388E+06	24.8± 25.4
14	1	36	20	0.028	10.3	5.844E+04	2.104E+06	13.1± 13.3
15	0	14	18	0.000	4.5	0.000E+00	9.090E+05	0.0± 0.0
16	0	9	12	0.000	4.3	0.000E+00	8.766E+05	0.0± 0.0
17	0	10	12	0.000	4.8	0.000E+00	9.740E+05	0.0± 0.0
18	0	5	9	0.000	3.2	0.000E+00	6.493E+05	0.0± 0.0
19	1	17	12	0.059	8.1	9.740E+04	1.656E+06	27.7± 28.5
20	0	8	9	0.000	5.1	0.000E+00	1.039E+06	0.0± 0.0
	9	313			6.8	4.000E+04	1.391E+06	

Area of basic unit = 8.789E-07 cm-2

CHI SQUARED = 11.87335 WITH 19 DEGREES OF FREEDOM
P(chi squared) = 89.1 %
CORRELATION COEFFICIENT = 0.527
VARIANCE OF SQR(Ns) = .3124098
VARIANCE OF SQR(Ni) = 1.217401

Ns/Ni = 0.029 ± 0.010
MEAN RATIO = 0.023 ± 0.008

POOLED AGE = 13.2 ± 4.5 Ma
MEAN AGE = 10.4 ± 3.6 Ma

Ages calculated using a zeta of 352.7 ± 3.9 for SRM612 glass
RHO D = 2.605E+06cm-2; ND = 11864

88 POS 120A - FIRE CREEK SS. - 12,501'

IRRADIATION LU023 SLIDE NUMBER 06
COUNTED BY: POS

No.	Ns	Ni	Na	RATIO	U(ppm)	RHOs	RHOi	F.T.AGE(Ma)
1	1	35	20	0.029	10.0	5.844E+04	2.045E+06	13.5± 13.7
2	1	20	16	0.050	7.2	7.305E+04	1.461E+06	23.5± 24.1
3	0	14	16	0.000	5.0	0.000E+00	1.023E+06	0.0± 0.0
4	0	10	9	0.000	6.4	0.000E+00	1.299E+06	0.0± 0.0
5	0	15	12	0.000	7.2	0.000E+00	1.461E+06	0.0± 0.0
6	1	21	16	0.048	7.5	7.305E+04	1.534E+06	22.4± 23.0
7	2	19	12	0.105	9.1	1.948E+05	1.851E+06	49.5± 36.8
8	0	9	8	0.000	6.5	0.000E+00	1.315E+06	0.0± 0.0
9	0	30	12	0.000	14.3	0.000E+00	2.922E+06	0.0± 0.0
10	0	36	20	0.000	10.3	0.000E+00	2.104E+06	0.0± 0.0
11	0	9	12	0.000	4.3	0.000E+00	8.766E+05	0.0± 0.0
12	0	6	9	0.000	3.8	0.000E+00	7.792E+05	0.0± 0.0
13	1	9	9	0.111	5.7	1.299E+05	1.169E+06	52.2± 55.0
14	0	17	20	0.000	4.9	0.000E+00	9.935E+05	0.0± 0.0
15	1	17	12	0.059	8.1	9.740E+04	1.656E+06	27.7± 28.5
16	0	12	9	0.000	7.6	0.000E+00	1.558E+06	0.0± 0.0
	7	279			7.5	3.859E+04	1.538E+06	

Area of basic unit = 8.789E-07 cm-2

CHI SQUARED = 12.37848 WITH 15 DEGREES OF FREEDOM
P(chi squared) = 65.0 %
CORRELATION COEFFICIENT = 0.206
VARIANCE OF SQR(Ns) = .2952411
VARIANCE OF SQR(Ni) = 1.134424

Ns/Ni = 0.025 ± 0.010
MEAN RATIO = 0.025 ± 0.010

POOLED AGE = 11.7 ± 4.5 Ma
MEAN AGE = 11.7 ± 4.5 Ma

Ages calculated using a zeta of 352.7 ± 3.9 for SRM612 glass
RHO D = 2.637E+06cm-2; ND = 11864

88 POS 122A - KINGAK SHALE - 9,435'

IRRADIATION LU023 SLIDE NUMBER 08
COUNTED BY: POS

No.	Ns	Ni	Na	RATIO	U(ppm)	RHOs	RHOi	F.T.AGE(Ma)
1	0	13	8	0.000	9.3	0.000E+00	1.899E+06	0.0± 0.0
2	1	12	12	0.083	5.7	9.740E+04	1.169E+06	39.2± 40.8
3	3	7	6	0.429	6.7	5.844E+05	1.364E+06	199.1±137.4
4	2	31	6	0.065	29.6	3.896E+05	6.039E+06	30.4± 22.2
5	14	91	10	0.154	52.2	1.636E+06	1.064E+07	72.2± 20.7
6	3	24	12	0.125	11.5	2.922E+05	2.338E+06	58.7± 36.0
7	15	95	12	0.158	45.4	1.461E+06	9.253E+06	74.1± 20.6
8	0	14	8	0.000	10.0	0.000E+00	2.045E+06	0.0± 0.0
9	1	25	6	0.040	23.9	1.948E+05	4.870E+06	18.8± 19.2
10	13	83	15	0.157	31.7	1.013E+06	6.467E+06	73.5± 21.9
11	0	14	16	0.000	5.0	0.000E+00	1.023E+06	0.0± 0.0
12	0	4	6	0.000	3.8	0.000E+00	7.792E+05	0.0± 0.0
13	0	6	10	0.000	3.4	0.000E+00	7.013E+05	0.0± 0.0
14	1	16	9	0.062	10.2	1.299E+05	2.078E+06	29.4± 30.3
15	1	11	6	0.091	10.5	1.948E+05	2.143E+06	42.7± 44.6
16	10	86	6	0.116	82.2	1.948E+06	1.675E+07	54.6± 18.3
17	7	95	30	0.074	18.2	2.727E+05	3.701E+06	34.7± 13.6
18	0	15	9	0.000	9.6	0.000E+00	1.948E+06	0.0± 0.0
19	5	74	12	0.068	35.4	4.870E+05	7.207E+06	31.8± 14.7
20	5	59	12	0.085	28.2	4.870E+05	5.746E+06	39.9± 18.6
	81	775			21.1	4.487E+05	4.293E+06	

Area of basic unit = 8.789E-07 cm-2

CHI SQUARED = 21.58282 WITH 19 DEGREES OF FREEDOM
P(chi squared) = 30.6 %
CORRELATION COEFFICIENT = 0.909
VARIANCE OF SQR(Ns) = 1.834569
VARIANCE OF SQR(Ni) = 7.775956

Ns/Ni = 0.105 ± 0.012
MEAN RATIO = 0.085 ± 0.022

POOLED AGE = 49.6 ± 5.8 Ma
MEAN AGE = 40.5 ± 10.4 Ma

Ages calculated using a zeta of 352.7 ± 3.9 for SRM612 glass
RHO D = 2.701E+06cm-2; ND = 11864

88 POS 123A - TOROK FM. - 8,849'

IRRADIATION LU023 SLIDE NUMBER 09
COUNTED BY: POS

No.	Ns	Ni	Na	RATIO	U(ppm)	RHOs	RHOi	F.T.AGE(Ma)
1	0	23	24	0.000	5.5	0.000E+00	1.120E+06	0.0± 0.0
2	1	32	16	0.031	11.5	7.305E+04	2.338E+06	14.7± 15.0
3	3	72	20	0.042	20.7	1.753E+05	4.208E+06	19.6± 11.6
4	1	10	12	0.100	4.8	9.740E+04	9.740E+05	47.0± 49.3
5	0	4	12	0.000	1.9	0.000E+00	3.896E+05	0.0± 0.0
6	1	8	16	0.125	2.9	7.305E+04	5.844E+05	58.7± 62.3
7	3	31	15	0.097	11.9	2.338E+05	2.415E+06	45.5± 27.5
8	2	20	20	0.100	5.7	1.169E+05	1.169E+06	47.0± 34.9
9	6	61	40	0.098	8.7	1.753E+05	1.782E+06	46.2± 19.8
10	3	21	30	0.143	4.0	1.169E+05	8.181E+05	67.0± 41.4
11	2	22	16	0.091	7.9	1.461E+05	1.607E+06	42.7± 31.6
12	0	11	20	0.000	3.2	0.000E+00	6.428E+05	0.0± 0.0
13	5	34	40	0.147	4.9	1.461E+05	9.935E+05	69.0± 33.1
14	6	62	30	0.097	11.9	2.338E+05	2.415E+06	45.5± 19.5
15	2	25	16	0.080	9.0	1.461E+05	1.826E+06	37.6± 27.7
16	1	8	20	0.125	2.3	5.844E+04	4.675E+05	58.7± 62.3
17	1	8	12	0.125	3.8	9.740E+04	7.792E+05	58.7± 62.3
18	3	32	40	0.094	4.6	8.766E+04	9.350E+05	44.1± 26.6
19	2	21	18	0.095	6.7	1.299E+05	1.364E+06	44.8± 33.1
20	0	15	20	0.000	4.3	0.000E+00	8.766E+05	0.0± 0.0
	42	520			6.8	1.123E+05	1.391E+06	

Area of basic unit = 8.789E-07 cm-2

CHI SQUARED = 10.28085 WITH 19 DEGREES OF FREEDOM
P(chi squared) = 94.6 %
CORRELATION COEFFICIENT = 0.777
VARIANCE OF SQR(Ns) = .602412
VARIANCE OF SQR(Ni) = 3.195221

Ns/Ni = 0.081 ± 0.013
MEAN RATIO = 0.079 ± 0.011

POOLED AGE = 38.8 ± 6.2 Ma
MEAN AGE = 38.2 ± 5.3 Ma

Ages calculated using a zeta of 352.7 ± 3.9 for SRM612 glass
RHO D = 2.733E+06cm-2; ND = 11864

88 POS 124A - TOROK FM. - 8,237'

IRRADIATION LU023 SLIDE NUMBER 10
COUNTED BY: POS

No.	Ns	Ni	Na	RATIO	U(ppm)	RHOs	RHOi	F.T.AGE(Ma)
1	3	27	12	0.111	12.9	2.922E+05	2.630E+06	52.2± 31.8
2	0	20	15	0.000	7.6	0.000E+00	1.558E+06	0.0± 0.0
3	7	102	16	0.069	36.6	5.113E+05	7.451E+06	32.3± 12.6
4	2	9	21	0.222	2.5	1.113E+05	5.009E+05	104.0± 81.3
5	5	53	12	0.094	25.3	4.870E+05	5.162E+06	44.4± 20.8
6	0	15	27	0.000	3.2	0.000E+00	6.493E+05	0.0± 0.0
7	9	58	20	0.155	16.6	5.259E+05	3.389E+06	72.8± 26.1
8	2	14	50	0.143	1.6	4.675E+04	3.273E+05	67.0± 50.7
9	6	128	15	0.047	49.0	4.675E+05	9.974E+06	22.1± 9.2
10	3	15	9	0.200	9.6	3.896E+05	1.948E+06	93.7± 59.3
11	0	16	24	0.000	3.8	0.000E+00	7.792E+05	0.0± 0.0
12	6	130	30	0.046	24.9	2.338E+05	5.065E+06	21.7± 9.1
13	2	13	40	0.154	1.9	5.844E+04	3.798E+05	72.2± 54.8
14	9	68	20	0.132	19.5	5.259E+05	3.974E+06	62.1± 22.1
15	0	12	25	0.000	2.8	0.000E+00	5.610E+05	0.0± 0.0
16	5	61	14	0.082	25.0	4.174E+05	5.092E+06	38.6± 17.9
17	2	15	20	0.133	4.3	1.169E+05	8.766E+05	62.6± 47.1
18	7	90	15	0.078	34.4	5.454E+05	7.013E+06	36.6± 14.4
19	0	12	18	0.000	3.8	0.000E+00	7.792E+05	0.0± 0.0
20	3	26	12	0.115	12.4	2.922E+05	2.532E+06	54.2± 33.1
	71	884			12.2	2.000E+05	2.490E+06	

Area of basic unit = 8.789E-07 cm-2

CHI SQUARED = 21.8865 WITH 19 DEGREES OF FREEDOM
P(chi squared) = 29.0 %
CORRELATION COEFFICIENT = 0.765
VARIANCE OF SQR(Ns) = 1.123067
VARIANCE OF SQR(Ni) = 8.050961

Ns/Ni = 0.080 ± 0.010
MEAN RATIO = 0.089 ± 0.015

POOLED AGE = 39.4 ± 4.9 Ma
MEAN AGE = 43.7 ± 7.6 Ma

Ages calculated using a zeta of 352.7 ± 3.9 for SRM612 glass
RHO D = 2.789E+06cm-2; ND = 11864

88 POS 125A - TOROK FM. - 5,006'

IRRADIATION LU023 SLIDE NUMBER 11
COUNTED BY: POS

No.	Ns	Ni	Na	RATIO	U(ppm)	RHOs	RHOi	F.T.AGE(Ma)
1	6	21	40	0.286	3.0	1.753E+05	6.136E+05	133.4± 61.8
2	5	22	50	0.227	2.5	1.169E+05	5.143E+05	106.3± 52.7
3	15	78	40	0.192	11.2	4.383E+05	2.279E+06	90.1± 25.4
4	4	19	24	0.211	4.5	1.948E+05	9.253E+05	98.6± 54.2
5	4	15	24	0.267	3.6	1.948E+05	7.305E+05	124.6± 70.1
6	5	21	40	0.238	3.0	1.461E+05	6.136E+05	111.4± 55.4
7	29	152	25	0.191	34.9	1.356E+06	7.106E+06	89.4± 18.2
8	2	15	12	0.133	7.2	1.948E+05	1.461E+06	62.6± 47.1
9	5	22	21	0.227	6.0	2.783E+05	1.224E+06	106.3± 52.7
10	6	60	40	0.100	8.6	1.753E+05	1.753E+06	47.0± 20.1
11	5	18	42	0.278	2.5	1.391E+05	5.009E+05	129.7± 65.6
12	4	20	40	0.200	2.9	1.169E+05	5.844E+05	93.7± 51.3
13	5	22	40	0.227	3.2	1.461E+05	6.428E+05	106.3± 52.7
14	6	23	30	0.261	4.4	2.338E+05	8.961E+05	121.9± 55.9
15	6	20	30	0.300	3.8	2.338E+05	7.792E+05	140.0± 65.2
16	2	13	40	0.154	1.9	5.844E+04	3.798E+05	72.2± 54.8
17	4	15	50	0.267	1.7	9.350E+04	3.506E+05	124.6± 70.1
18	4	16	40	0.250	2.3	1.169E+05	4.675E+05	116.9± 65.4
19	8	29	30	0.276	5.5	3.117E+05	1.130E+06	128.8± 51.5
20	5	21	30	0.238	4.0	1.948E+05	8.181E+05	111.4± 55.4
	130	622			5.2	2.208E+05	1.057E+06	

Area of basic unit = 8.789E-07 cm-2

CHI SQUARED = 6.736065 WITH 19 DEGREES OF FREEDOM
P(chi squared) = 99.5 %
CORRELATION COEFFICIENT = 0.964
VARIANCE OF SQR(Ns) = .746221
VARIANCE OF SQR(Ni) = 4.450305

Ns/Ni = 0.209 ± 0.020
MEAN RATIO = 0.226 ± 0.012

POOLED AGE = 102.3 ± 9.9 Ma
MEAN AGE = 110.6 ± 5.8 Ma

Ages calculated using a zeta of 352.7 ± 3.9 for SRM612 glass
RHO D = 2.797E+06cm-2; ND = 11864

88 POS 126A - NANUSHUK GROUP - 3,078'

IRRADIATION LU023 SLIDE NUMBER 12
COUNTED BY: POS

No.	Ns	Ni	Na	RATIO	U(ppm)	RHOs	RHOi	F.T.AGE(Ma)
1	12	40	40	0.300	5.7	3.506E+05	1.169E+06	140.0± 46.1
2	5	22	50	0.227	2.5	1.169E+05	5.143E+05	106.3± 52.7
3	7	21	12	0.333	10.0	6.818E+05	2.045E+06	155.4± 67.8
4	4	20	24	0.200	4.8	1.948E+05	9.740E+05	93.7± 51.3
5	2	15	18	0.133	4.8	1.299E+05	9.740E+05	62.6± 47.1
6	5	22	15	0.227	8.4	3.896E+05	1.714E+06	106.3± 52.7
7	6	27	15	0.222	10.3	4.675E+05	2.104E+06	104.0± 47.0
8	2	12	12	0.167	5.7	1.948E+05	1.169E+06	78.1± 59.7
9	9	45	18	0.200	14.3	5.844E+05	2.922E+06	93.7± 34.2
10	6	45	40	0.133	6.5	1.753E+05	1.315E+06	62.6± 27.2
11	8	54	30	0.148	10.3	3.117E+05	2.104E+06	69.5± 26.4
12	4	20	36	0.200	3.2	1.299E+05	6.493E+05	93.7± 51.3
13	4	35	36	0.114	5.6	1.299E+05	1.136E+06	53.7± 28.3
14	6	24	30	0.250	4.6	2.338E+05	9.350E+05	116.9± 53.4
15	2	10	28	0.200	2.0	8.348E+04	4.174E+05	93.7± 72.6
16	2	10	40	0.200	1.4	5.844E+04	2.922E+05	93.7± 72.6
17	6	41	16	0.146	14.7	4.383E+05	2.995E+06	68.7± 30.0
18	4	16	40	0.250	2.3	1.169E+05	4.675E+05	116.9± 65.4
19	3	20	12	0.150	9.6	2.922E+05	1.948E+06	70.4± 43.6
20	5	19	30	0.263	3.6	1.948E+05	7.402E+05	123.0± 61.8
	102	518			5.5	2.200E+05	1.117E+06	

Area of basic unit = 8.789E-07 cm-2

CHI SQUARED = 7.63678 WITH 19 DEGREES OF FREEDOM
P(chi squared) = 99.0 %
CORRELATION COEFFICIENT = 0.757
VARIANCE OF SQR(Ns) = .3122036
VARIANCE OF SQR(Ni) = 1.520991

Ns/Ni = 0.197 ± 0.021
MEAN RATIO = 0.203 ± 0.013

POOLED AGE = 97.5 ± 10.6 Ma
MEAN AGE = 100.6 ± 6.5 Ma

Ages calculated using a zeta of 352.7 ± 3.9 for SRM612 glass
RHO D = 2.829E+06cm-2; ND = 11864

88 POS 127A - NANUSHUK GROUP - 2,632'

IRRADIATION LU023 SLIDE NUMBER 13
COUNTED BY: POS

No.	Ns	Ni	Na	RATIO	U(ppm)	RHOs	RHOi	F.T.AGE(Ma)
1	4	14	24	0.286	3.3	1.948E+05	6.818E+05	133.4± 75.7
2	12	41	40	0.293	5.9	3.506E+05	1.198E+06	136.6± 44.9
3	5	29	16	0.172	10.4	3.652E+05	2.118E+06	80.8± 39.2
4	7	21	12	0.333	10.0	6.818E+05	2.045E+06	155.4± 67.8
5	9	24	36	0.375	3.8	2.922E+05	7.792E+05	174.5± 68.3
6	2	16	18	0.125	5.1	1.299E+05	1.039E+06	58.7± 44.0
7	16	77	21	0.208	21.0	8.905E+05	4.285E+06	97.3± 26.8
8	6	28	15	0.214	10.7	4.675E+05	2.182E+06	100.3± 45.1
9	4	43	21	0.093	11.7	2.226E+05	2.393E+06	43.7± 22.9
10	9	41	18	0.220	13.1	5.844E+05	2.662E+06	102.7± 37.8
11	10	41	36	0.244	6.5	3.247E+05	1.331E+06	114.0± 40.3
12	8	71	30	0.113	13.6	3.117E+05	2.766E+06	52.9± 19.8
13	2	14	8	0.143	10.0	2.922E+05	2.045E+06	67.0± 50.7
14	4	38	36	0.105	6.1	1.299E+05	1.234E+06	49.5± 26.0
15	9	40	20	0.225	11.5	5.259E+05	2.338E+06	105.3± 38.9
16	2	15	28	0.133	3.1	8.348E+04	6.261E+05	62.6± 47.1
17	6	25	10	0.240	14.3	7.013E+05	2.922E+06	112.2± 51.0
18	6	42	15	0.143	16.1	4.675E+05	3.273E+06	67.0± 29.3
19	4	18	30	0.222	3.4	1.558E+05	7.013E+05	104.0± 57.5
20	3	19	12	0.158	9.1	2.922E+05	1.851E+06	74.1± 46.0
	128	657			8.4	3.354E+05	1.722E+06	

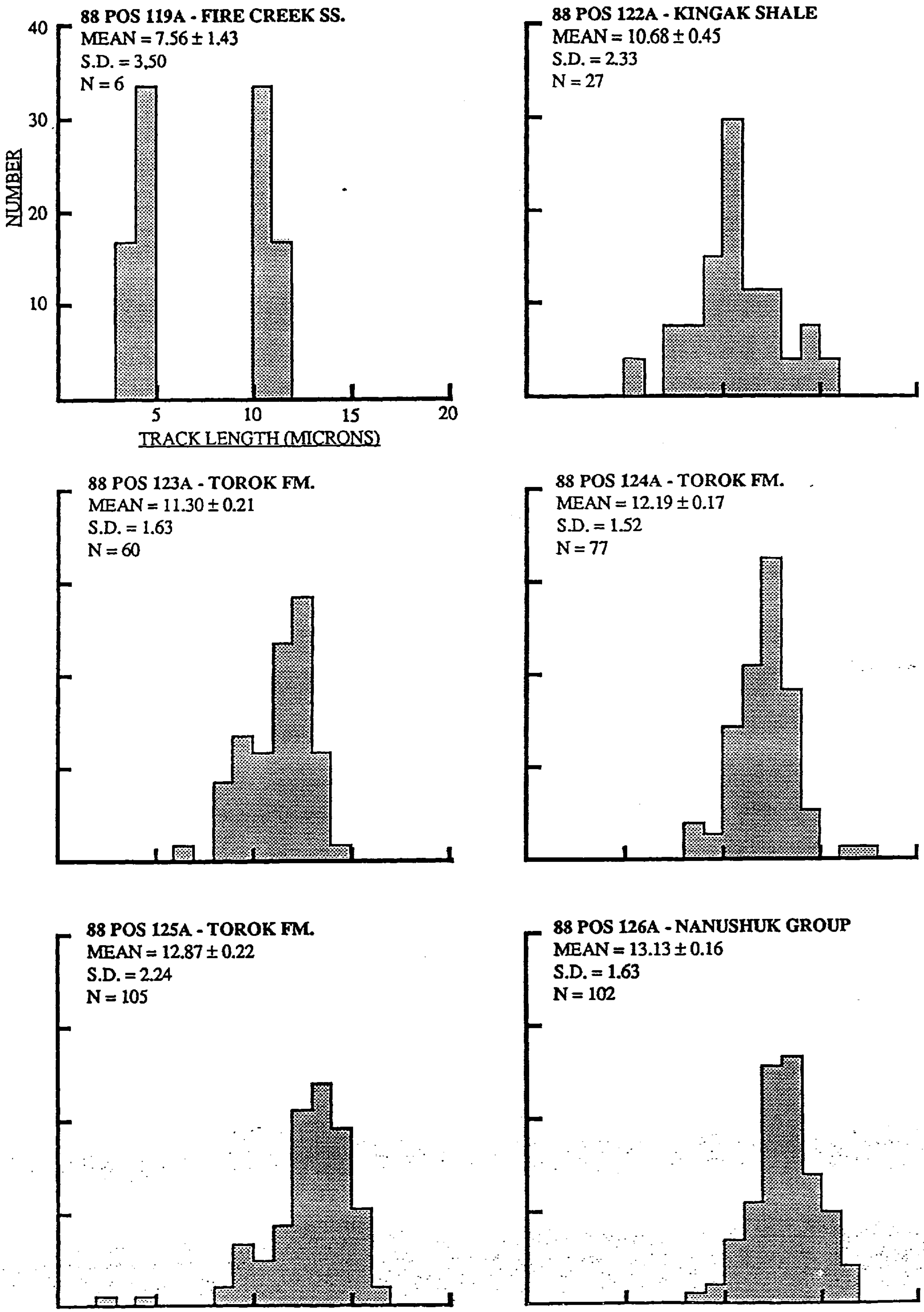
Area of basic unit = 8.789E-07 cm-2

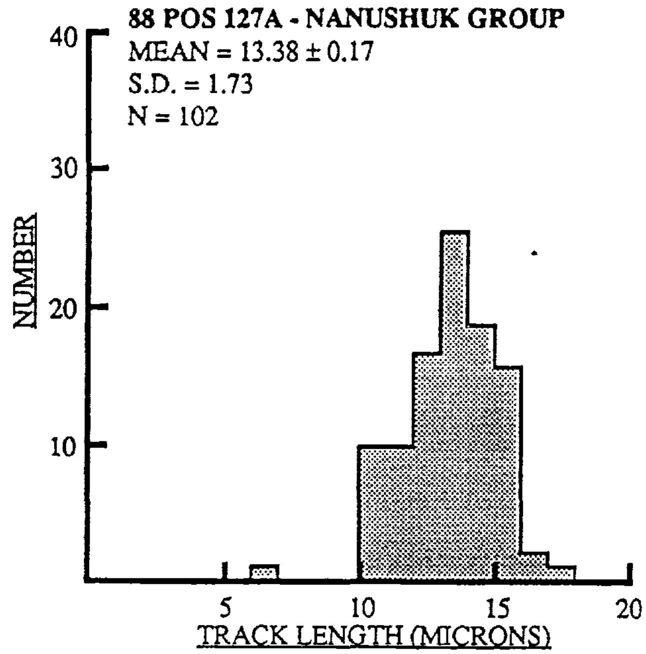
CHI SQUARED = 14.7022 WITH 19 DEGREES OF FREEDOM
P(chi squared) = 74.1 %
CORRELATION COEFFICIENT = 0.736
VARIANCE OF SQR(Ns) = .5058557
VARIANCE OF SQR(Ni) = 2.123895

Ns/Ni = 0.195 ± 0.019
MEAN RATIO = 0.202 ± 0.018

POOLED AGE = 97.6 ± 9.5 Ma
MEAN AGE = 101.2 ± 8.8 Ma

Ages calculated using a zeta of 352.7 ± 3.9 for SRM612 glass
RHO D = 2.861E+06cm-2; ND = 11864


88 POS 119A - FIRE CREEK SS.
MEAN = 7.56 ± 1.43
S.D. = 3.50
N = 6
NUMBER
40
30
20
10
5
10
15
20
TRACK LENGTH (MICRONS)
88 POS 122A - KINGAK SHALE
MEAN = 10.68 ± 0.45
S.D. = 2.33
N = 27
88 POS 123A - TOROK FM.
MEAN = 11.30 ± 0.21
S.D. = 1.63
N = 60
88 POS 124A - TOROK FM.
MEAN = 12.19 ± 0.17
S.D. = 1.52
N = 77
88 POS 125A - TOROK FM.
MEAN = 12.87 ± 0.22
S.D. = 2.24
N = 105
88 POS 126A - NANUSHUK GROUP
MEAN = 13.13 ± 0.16
S.D. = 1.63
N = 102


88 POS 127A - NANUSHUK GROUP
MEAN = 13.38 ± 0.17
S.D. = 1.73
N = 102
NUMBER
40
30
20
10
5
10
15
20
TRACK LENGTH (MICRONS)

APPENDIX A

FISSION TRACK ANALYSIS: A SUMMARY OF THE TECHNIQUE AND INTERPRETATION OF RESULTS

INTRODUCTION

Fission tracks are damage zones formed as charged particles, produced by fission of a heavy atom (^{232}Th, ^{235}U, and ^{238}U), pass through a crystal lattice. It is assumed for all practical purposes that all fission tracks have come from ^{238}U because ^{232}Th and ^{235}U possess very low fission decay rates compared to ^{238}U (Naeser, 1979a). ^{238}U decays by both spontaneous fission and alpha particle emission but alpha particles themselves do not create tracks in natural minerals (Fleischer *et al.*, 1975).

The density of spontaneous tracks (fossil tracks) is proportional to the length of time during which tracks have accumulated and to the ^{238}U concentration of the sample. The concentration of ^{238}U can be determined by irradiating the sample alongside a standard in a nuclear reactor, using a monitored thermal neutron flux. Thermal neutrons in the reactor induce fission in a fraction of ^{235}U present in the sample. A count of the induced tracks produced from the decay of ^{235}U can be related to the ^{238}U concentration using the constant ^{235}U/^{238}U ratio in natural materials (7.252×10^{-3}). By determining the ratio of fossil tracks to induced tracks, a geological age can be determined. The ratio of ^{238}U to fission track density is analogous to the ratio of parent to daughter isotopes in other radiometric dating systems.

FISSION TRACKS AND FISSION TRACK TECHNIQUES

The Formation of a Fission Track

A fission track is formed when a nucleus of a heavy element such as uranium undergoes fission. Fission decay results in two fast-moving highly-charged fission fragments recoiling from each other in opposite directions due to electrostatic repulsion. The best explanation for the formation of fission tracks is the "ion explosion spike" (Fleischer *et al.*, 1975) (Fig. A1). A "burst" of ionization along the path of the charged particles creates an electrostatically unstable array of adjacent ions which eject one another from their normal sites into interstitial positions. As the fission fragment passes, it strips electrons and leaves a zone of net positive charge in its wake. This causes the remaining positively-charged ions along the particles path to repel each other, forming the track or damage zone. Some have speculated that a phase change occurs in the vicinity of the fission track.

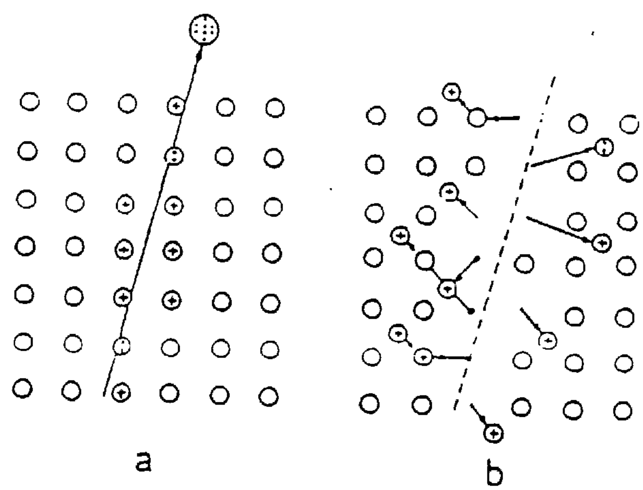


Figure A1. The ion explosion spike mechanism for track formation in a simple crystalline solid; (a) atoms are ionized by passage of a massive charged particle (fission fragment), (b) causing instability and ejecting ions into the lattice by mutual repulsion (after Fleischer *et al.*, 1975).

The resultant track is only a few angstroms wide and ~10-20 μm long (Naeser, 1979a). It remains stable in all insulating solids, but conducting and semi-conducting solids do not retain tracks as movement of electrons rapidly neutralizes the ions produced. These tracks can be observed by transmission electron microscopy but the electron beam anneals them quickly. It is also possible to observe them under a petrographic microscope once the tracks have been revealed by chemical etching.

Track Etching

Fission tracks are made visible by chemical etching because the etchant preferentially attacks the highly disordered (glassy?) material along the track. The geometry of track etching is determined by the simultaneous action of two etching processes (Gleadow, 1984). These are the rate of etching along the particle track surface at a linear rate (V_T) and the rate of etching along an undamaged surface, or bulk etching rate (V_G). Selective etching of a track depends on V_T being greater than V_G, with the shape of the resulting track being dependent on the difference between these two etching rates. For example, if $V_T >> V_G$, a narrow conical track is produced (Fig. A2). If V_T is only slightly greater

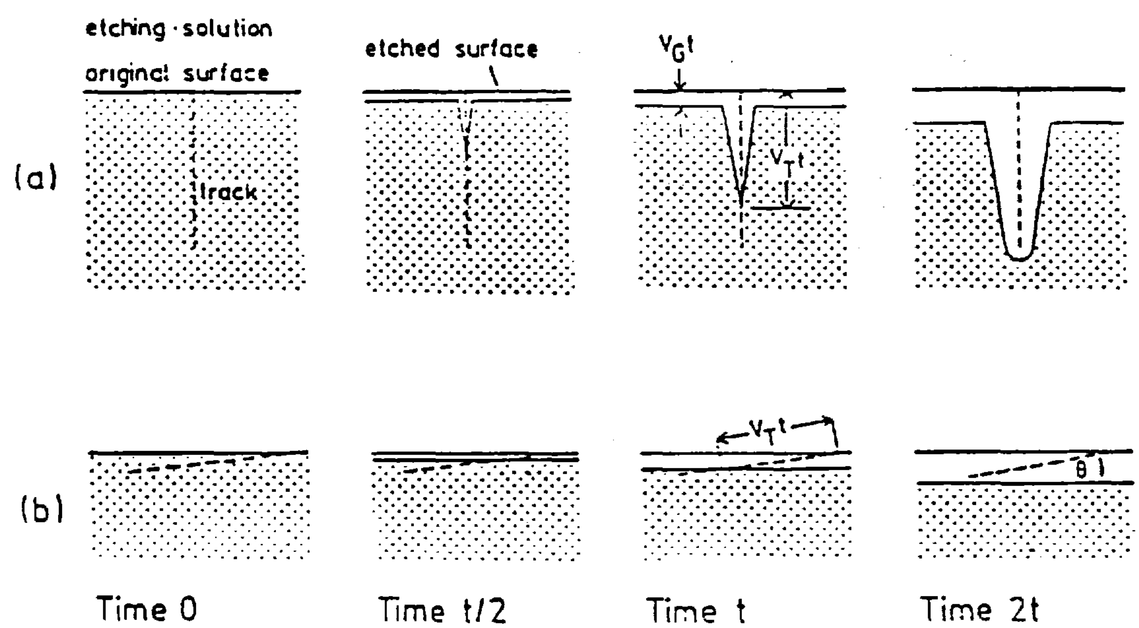


Figure A2. Track geometry showing $V_G t$ (bulk surface etching with time) and $V_T t$ (track etching with time). Tracks intersecting the surface at angles less than the critical angle ø will not be revealed. See text for explanation (from Gleadow, 1984).

than V_G, a shallow, wide, poorly defined track results. Another factor that controls the observation of tracks is the angle at which a track intersects the surface. Tracks intersecting the surface at less than the minimum intersection angle ø are not revealed by etching because the vertical component of V_T is not as great as V_G (Fleischer and Price, 1963) (Fig. A2). Therefore, where ø is greater than zero, an etching efficiency (π) exists, defined as the fraction of tracks intersecting a given surface that are actually etched on the surface. Only those tracks intersecting at angles greater than ø (defined by $\sin ø = V_T/V_G$) will be revealed by etching.

The concepts of V_T and V_G explain track etching well for isotropic minerals, however V_G is anisotropic in most minerals (Fleischer *et al.*, 1975). This anisotropy is reduced by accumulating radiation damage from the alpha decay of uranium and thorium in the host mineral (Gleadow, 1978). Working with sphene, Gleadow, (1978) found that the mineral became more isotropic with accumulating radiation damage causing progressive change in the etching characteristics of fission tracks. The consequences of anisotropic etching (shape of etched fission tracks with different crystallographic orientations and different V_G values on different crystallographic planes) and accumulated radiation damage are discussed in more detail by Gleadow (1981) and Gleadow (1984).

Etching Conditions

In order to reveal tracks clearly it is important to establish proper etching conditions. Under-etching results in tracks being faint and easy to miss so that track density is underestimated. Over-etching makes it difficult to distinguish tracks from other etch features or intersecting tracks. Apatites of widely different composition and age seem to be very consistent in their etching behavior, unlike sphene and zircon, therefore an etching time of approximately 20 seconds in 5 mol HNO_3 at 20°C is sufficient to reveal fission tracks (Gleadow, 1984). Sphene and zircon have highly variable etching times dependent on general radiation damage plus a number of other compositional and crystallographic features (Gleadow, 1978; Hurford and Green, 1982; Gleadow, 1984).

Fleischer *et al.* (1975) has summarized the characteristics of fission tracks which make them easily distinguishable from dislocations and other spurious etch pits. Fission tracks are randomly orientated linear defects of finite length with a limited thermal stability, and should have a statistical distribution related to spatial variation of uranium concentration.

Fission Track Dating Methods

Different fission track dating methods are described by Hurford and Green (1982) and Gleadow (1981). These include the population method and the external detector method (EDM). In the population method, the spontaneous and induced track densities are measured on two aliquots of the separated mineral grains. In the EDM, spontaneous and induced tracks are measured in exactly matching areas from the same internal surface of an individual crystal.

The EDM is now the most commonly used technique for fission track mineral dating. There are many advantages of the EDM, including the ability to date and analyze individual grains and its adaptability to automation. It also requires less counting times, gives more reproducible results, and requires less complicated handling after irradiation.

The External Detector Method

In this method spontaneous tracks are measured on an internal surface of a mineral grain. During irradiation induced tracks from ^{235}U are registered on an external surface of a detector mineral held in contact with the same surface on which the spontaneous tracks are counted. This detector, usually a sheet of low-uranium muscovite (<5 ppb), is subsequently etched to reveal the registered tracks. Spontaneous and induced tracks are counted in exactly matching areas from the same surface plane of an individual crystal so that inhomogeneity in uranium concentration between grains and within grains is not a problem as it is with the population method.

Since dating involves determining ages for individual grains it is important to avoid selecting grains that are badly etched or contain dislocations. When selecting grains one should count only grains which have a low V_G, identified by the presence of sharp polishing scratches. Scratches indicate a very slow bulk etching rate for that exposed surface and hence a high etching efficiency for tracks (Gleadow, 1978). Other features one looks for when selecting grains include alignment of etch pits elongated along the c-axis, and optical characteristics which indicate that the surface is parallel to the c-axis.

Gleadow (1978) and Hurford and Green (1982) discuss the EDM in more detail. Hurford and Green (1982) also conclude that sphene and zircon, which are known to accumulate alpha-recoil damage, can only be dated reliably by the EDM. This is because laboratory annealing used in the population method removes the alpha-recoil damage as well the spontaneous fission tracks thereby restoring the initial highly anisotropic pattern of bulk etch rates. An overestimation of age with sphene can result because etching of the induced tracks in the annealed sphene will be anisotropic and weakly etched tracks may be overlooked during counting.

THE FISSION TRACK EQUATION, ZETA CALIBRATION, AND ERROR ANALYSIS

The Fission Track Equation

The fission track age equation is a specialized form of the general age equation used in all other forms of radiometric dating (Gleadow, 1984). In fission track dating however, the ratio of daughter atoms to parent atoms remaining is a function of the ratio of spontaneous to induced track densities of the form (Price and Walker, 1963):

$$T = \frac{1}{\lambda_D} ln \left(1 + \frac{\lambda_D \phi \sigma I \rho_s}{\lambda_f \rho_i} \right) \qquad (1)$$

I = isotopic ratio $^{235}U/^{238}U = 7.252 \times 10^{-3}$ (Conran and Adler, 1976).
λ_D = total decay constant for $^{238}U = 1.55125 \times 10^{10}\ yr^{-1}$ (Jaffey *et al.*, 1971).
λ_f = spontaneous fission decay constant of ^{238}U; two values, 6.85 or $8.42 \times 10^{-17} yr^{-1}$ (Fleischer and Price, 1964; Galliker *et al.*, 1970); see following page for explanation.
σ = thermal neutron cross section for $^{235}U = 580 \times 10^{-24} cm^2$ (Hannah *et al.*, 1969).
ϕ = thermal neutron fluence.
ρ_s = spontaneous track density.
ρ_i = induced track density.

Two or more standard glass/mica pairs are included in each irradiation package to monitor neutron fluence and the possible presence of a gradient along the package. The standard glass (NBS glass SRM612) contains uniform U concentration (~50 ppm) that produces manageable track densities in the mica detectors. The flux is directly related to the track density in the mica ρ_d by:

$$\phi = B\rho_d \qquad (2)$$

where B is a calibration constant for the standard glass (~ 5.736×10^9; Hurford and Green, 1983).

To determine an age using equation (1) requires the measurement of ρ_s and ρ_i, the determination of neutron fluence (ϕ), and the use of the constants B and λ_f. The use of this equation, its systematics, and calibrations have been reviewed by Hurford and Green (1982).

The value of the spontaneous fission decay constant for ^{238}U (λ_f) has been in doubt for some time. Fleischer and Price (1964) reported a value 6.85 ($\pm$ 0.20) x $10^{-17} yr^{-1}$ based on a comparison of fission track dates of tektites with K-Ar dates. However, when the effect of track fading, causing decreased ages, is taken into consideration, a value of $8.4 \times 10^{-17} yr^{-1}$ is obtained (Storzer and Wagner, 1971). A more precise determination is by Galliker *et al.*, (1970), who reported a value of 8.46 (± 0.06) x $10^{-17} yr^{-1}$. This value for λ_f was confirmed by Storzer (1970) and Wagner *et al.*, (1975). Both values ($6.85 \times 10^{-17} yr^{-1}$ and $8.46 \times 10^{-17} yr^{-1}$) have been used for dating by the fission track method (e.g. Gleadow and Lovering, 1974; Bar *et al.*,1974).

The value of B is often determined against independent measurements of the fluence or by reference to fission track dating of an age standard using an assumed value of λ_f. Green and Hurford (1984), report that neutron dosimetry using activation foils can be extremely unreliable. They also report that reproducibility of fluence calibrations between different laboratories is poor and that this is expected because in many cases determinations of λ_f have depended of fluence measurements (Hurford and Green, 1982). They concluded that any value of λ_f calculated using a system of thermal neutron dosimetry is only valid for that system.

Zeta Calibration

Fission track dates are subject to systematic errors arising from the uncertainty of λ_f and from difficulties with measurements of the neutron dose (ϕ). Hurford and Green (1982) proposed that until independent values of λ_f and ϕ are known, fission track dating should be empirically calibrated against independently known ages. Substituting equation (2) into equation (1) gives:

$$T = \frac{1}{\lambda_D} ln \left(1 + \frac{\rho_s}{\rho_i} \sigma I \lambda_D \left(\frac{B\rho_d}{\lambda_f}\right)\right) \qquad (3)$$

The constants in equation (3), except for λ_D (which effectively cancels out for young ages under 100 Ma) can be grouped into a single factor, "zeta" (ζ) which is calibrated directly from age standards.

$$\zeta = \frac{e^{\lambda_D T_{STD}} - 1}{\lambda_D (\rho_s/\rho_i)_{STD} \rho_d} \qquad (4)$$

Equation (3) becomes:

$$T = \frac{1}{\lambda_D} ln \left(1 + \lambda_D \zeta \frac{\rho_s}{\rho_i} \rho_d \right) \qquad (5)$$

Ratios of counts obtained over different standard glasses in common use in laboratories have been given by Hurford and Green (1983) and Green (1985).

Personal Zeta Calibration

I used three apatite standards for zeta calibration before any unknowns were counted. The three standards were the Fish Canyon Tuff (27.9 ± 0.7 Ma), Durango apatite (31.4 ± 0.5 Ma), and Mt. Dromedary apatite (98.7 ± 1.1 Ma). These three standards are discussed by Hurford and Green (1983) and Green (1985). My results are listed Table A1; the weighed mean zeta of 352.7 was used when determining unknown apatite ages in this study.

Determination of Error

The fundamental assumption of fission track statistics is that track counts, like radioactive decay, will follow a poisson distribution. The "conventional analysis" of errors(e.g. Lindsay *et al.*, 1975) assumes that no further sources of variation are present in the measurement of track densities. Green (1981), in his discussion on the use of statistics in fission track dating, discusses this assumption in detail. For a poisson distribution the

Table A1. Fission Track Counting of Standards for Personal Zeta Determination

Sample number	Number of grains	Standard track density ($x10^6cm^{-2}$)	Fossil track density ($x10^5cm^{-2}$)	Induced track density ($x10^6cm^{-2}$)	Correlation coefficient	Zeta
Durango apatite						
8122-3B	20	1.422 (321)	1.987 (2353)	1.456	0.824	324.5
8122-3A	15	1.422 (218)	1.700 (1927)	1.503	0.354	391.3
8122-3B	15	1.422 (234)	2.200 (1734)	1.630	0.981	328.1
				***Sample Mean Zeta* = 348.0**		
Fish Canyon tuff						
72N8-24	20	1.422 (336)	2.192 (2856)	1.863	0.754	333.1
72N8-01	20	1.422 (298)	1.860 (2845)	1.775	0.903	374.1
				***Sample Mean Zeta* = 353.6**		
Mt. Dromedary apatite						
8322-39	20	1.422 (884)	10.57 (2216)	2.651	0.781	350.7
8322-42	20	1.422 (767)	8.706 (2004)	2.275	0.771	365.5
8322-39	20	1.422 (775)	12.64 (1962)	3.201	0.857	354.1
				***Sample Mean Zeta* = 357.8**		
				Overall Mean Zeta =352.7		

Number of tracks counted are given in parenthesis. Standard and induced track densities are measured on mica detectors, and fossil track densities on internal mineral surfaces.

standard deviation S of a track count is given by the square root of the total number of tracks counted N:

$$S = \sqrt{N} \quad (6)$$

A standard deviation can be assigned to each track density measurement used in calculating a fission track age. These errors are combined to give the standard deviation of the age S_T:

$$S_T = T \sqrt{(1 / N_s) + (1 / N_i) + (1 / N_d)} \quad (7)$$

where N_s, N_i, and N_d are the total number of tracks counted for spontaneous, induced, and standard glass track densities. Other non-poissonian sources of variation are possible

(Green, 1981; see below) so the conventional analysis (equation 7) is actually a limiting best case.

The EDM is designed so that sampling problems should be eliminated because both ρ_s and ρ_i ideally originate from the same amount of uranium. Therefore, ρ_s and ρ_i should give approximately the same ratio within the variation allowed by the poisson distribution. However, when using the EDM, some experimental factors can make this "ideal case" unattainable:

[1] Careless counting of track-like features as tracks leads to an overestimate of ρ_s. This results in determination of an incorrect older age. Experience in the careful identification of tracks is necessary to overcome this factor.

[2] Poor contact between the grain mount and mica detector results in a lower ρ_i as fewer induced tracks are recorded in the detector. This leads to a higher ρ_s/ρ_i ratio and hence an older age. Bad contact over a large region of the mount can be recognized by the absence of shallow-dipping tracks and blurred replicas of grain boundaries in the mica. Apatite grains adjacent to zircon grains should not be counted as the higher relief of the zircon may result in poor contact locally and a decrease in ρ_i.

[3] High track densities make determination of true ρ_s/ρ_i difficult. A high spontaneous track density makes determination of the correct ρ_s difficult whereas a high induced track density does the same for ρ_i.

[4] A low ρ_i makes location of the grain replica and the correct counting area difficult and in some cases, next to impossible. This can be overcome by subjecting the sample to sufficiently large neutron fluences in the reactor.

[5] Incomplete etching of tracks leads to an underestimate of either ρ_i or ρ_s. Overetching may also result in an underestimate of either ρ_i or ρ_s as it is difficult in this case to

distinguish between tracks when they overlap. Overetching also results in the loss of short tracks.

[6] Spontaneous tracks may not be completely revealed. Zircon or sphene grains containing different spontaneous track densities or compositions will etch at different rates due to differing degrees of alpha damage. Therefore, at any given etch time, tracks will be completely revealed only for a limited range of ρ_s. Below this range, tracks are incompletely revealed, whereas at high ρ_s tracks are lost. Therefore at either low or high track densities, the measured values may be depressed, leading to low ρ_s/ρ_i ratios.

[7] Incorrect identification of the crystal or mica "mirror image" may yield totally incorrect ρ_s/ρ_i ratios. This problem can be eliminated by using a meticulous and careful technique.

[8] Spatial variation of the thermal neutron fluence may occur in the nuclear reactor and cause problems (Burchart, 1981). Standard glasses, included within a package of irradiated samples, are used to determine ρ_d and check on uniformity of fluence on a scale of centimeters. If the neutron fluence is not consistent on this scale, this might introduce an additional variation in ρ_s/ρ_i.

[9] Uranium may be vertically heterogeneous in the apatite grain (Burchart, 1981): ρ_i is measured in a mica detector exposed to fissions occurring below the sample surface, while ρ_s originates from fissions occurring both above and below the exposed sample surface. Therefore, in relating ρ_s to ρ_i, it is assumed that the amount of uranium above and below the sample surface is identical over the range of a fission event (~15-20 μm).

All of the above experimental factors are capable of introducing non-poissonian variations to or errors in the measured values of ρ_i and ρ_s, and, therefore, to the final age determination. However, with experience and careful sample preparation, factors [1] through [7] should be neutralized. Factors [8] and [9] plus contamination may be impossible to identify. The conventional method (equation 7) allows no check to be made on the way in which the data are affected by the above factors (Green, 1981). Thus, the final estimate of ρ_s/ρ_i may be strongly affected by data with a non-poissonian variation.

A χ^2 test can be used to test whether variation is present in excess of that predicted from poisson statistics and determines whether or not the data represents a single population (Galbraith, 1981). In geological situations, failure of the χ^2 test usually indicates that some external factor is acting on the variation of ρ_s/ρ_i. This is not always the case. Green (1985) has shown that an age determination can fail the χ^2 test by chance alone when non-poissonian errors were not present. For those instances when the value of χ^2 was not acceptable, Green (1981) determined that the mean of individual grain ratios of ρ_s/ρ_i ($\pm$ 1σ) takes into account non-poissonian variation where present and gives a more realistic estimate of the precision of the determination of ρ_s/ρ_i. The value of ρ_s/ρ_i is then:

$$\rho_s/\rho_i = \left(\frac{(\rho_s/\rho_i)}{n}\right) \qquad (8)$$

and its standard deviation is:

$$\sigma(\rho_s/\rho_i) = \frac{\sqrt{\Sigma\,(\rho_s/\rho_i)^2 - (\,\Sigma\,(\rho_s/\rho_i))^2}}{n(n-1)} \qquad (9)$$

The same analysis is often applied to results obtained by both the EDM and the population method. While this is valid for the EDM in most cases, it will be valid for the population method only in the case where the uranium concentration is the same for all the grains. Where there is a variation in uranium between grains, which is likely in most cases, the uncertainty calculated from equation (7) will be an underestimate.

APATITE FISSION TRACK LENGTHS

The length of fission tracks is an important parameter because tracks decrease in length (anneal) in response to time and temperature (Wagner and Storzer, 1972) and hence can be used as geothermometers. During the annealing of fission tracks, the effects of both time and temperature are important. A higher temperature for a shorter period of time can anneal tracks the same amount as a lower temperature over a longer time span.

Fission Track Annealing

Annealing has been discussed in detail by several authors: laboratory annealing by Naeser and Faul (1969), Storzer and Wagner (1971), and Wagner (1986); natural annealing by Naeser (1979a), and Gleadow and Duddy (1981); and fission track length annealing by Green *et al.* (1985a, 1986).

Laboratory Annealing Studies:: In laboratory annealing studies, a mineral is heated for varying periods of time at different temperatures. The degree of observed track density reduction with time and temperature is presented on an Arrhenius plot which relates the logarithm of time to the inverse of temperature. Early studies investigating the annealing properties of apatite found that heating apatite for a period of one hour produced total track annealing between 250° and 350°C (Naeser and Faul, 1969; Wagner, 1968). An Arrhenius plot representing the data (Figure A3: from Naeser and Faul, 1969), could then be used to extrapolate to a time period of 1 m.y. where 100% annealing would occur at ~175°C. The slope of the lines on the plot increase from that for 100% track retention to that for total track loss, with the difference in the slope of these two extremes ranging by a factor of 2 or 3 (Green *et al.*, 1985a). This *fanning array* has been interpreted in terms of activation energies increasing with degree of annealing (Storzer and Wagner, 1971). However, in another study, Wagner (1986), found a parallel-type Arrhenius plot describing a single activation energy when he carried out an annealing experiment on a single apatite crystal.

Natural Annealing Studies: A more direct way to study fission track annealing in apatite under geologic conditions is to look at the change in apatite age with depth in a drill hole (Naeser, 1981; Gleadow and Duddy, 1981). In three studies (Naeser and Forbes,

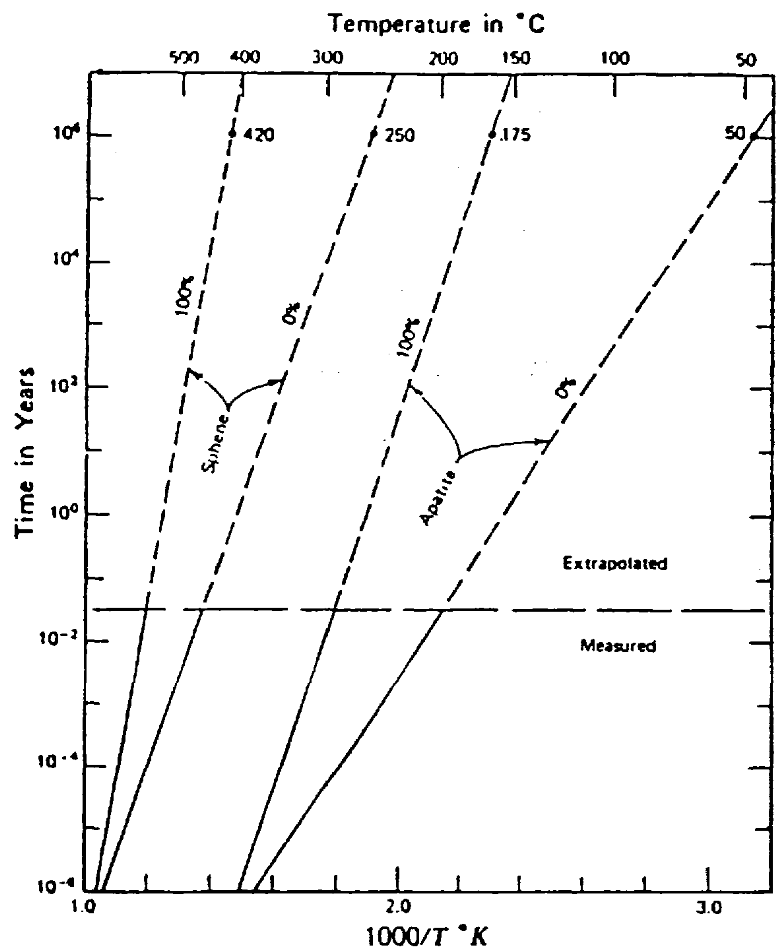


Figure A3. Results of a laboratory study of fading of fission tracks in apatite and sphene. The lines marked 0% indicate temperature and time periods in which no tracks are lost. The lines marked 100% indicate temperature and time periods at which all tracks are lost (from Naeser and Faul, 1969).

1976; Naeser, 1979a; Gleadow and Duddy, 1981), apatite fission track ages relative to depth in drill holes were reported. Naeser and Forbes (1976) found that apatite fission track ages decreased from 100 Ma at the surface to 12 Ma at 3000 m (~95°C present downhole temperature) in the Eielson Air Force Base, Alaska, deep drill hole. Naeser (1979a) reported a zero apparent age at 2000 m depth (~135°C present downhole temperature) from the Los Alamos, New Mexico, geothermal test wells 1 and 2. Gleadow and Duddy (1981), studying apatites from drill-holes located in the Otway Basin of southeastern Australia, identified both the top and the base of the track annealing zone. In this basin, stratigraphic evidence indicates that the sediments reached their maximum depth of burial at ~30 Ma and have essentially remained at this depth in a uniform temperature regime since then. Apatite ages start to decrease downhole at ~60°C (Fig. A4), are reduced by about half at ~95°C, and reach zero at ~125°C. The entire partial stability zone was therefore revealed. Combining their results with laboratory data from Wagner (1968) and Naeser and Faul (1969), Gleadow and Duddy (1981) constructed an Arrhenius plot (Fig.

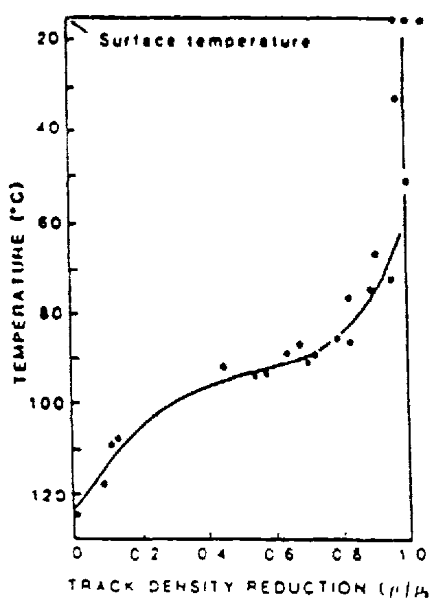


Figure A4. Variation in apparent apatite fission track age with down-hole temperature in wells of the Otway Basin, South Australia. Ages here are expressed as a fraction of their original age (120 Ma) giving a measure of ρ/ρ_0, the ratio of fission track density after and before natural annealing (from Gleadow and Duddy, 1981).

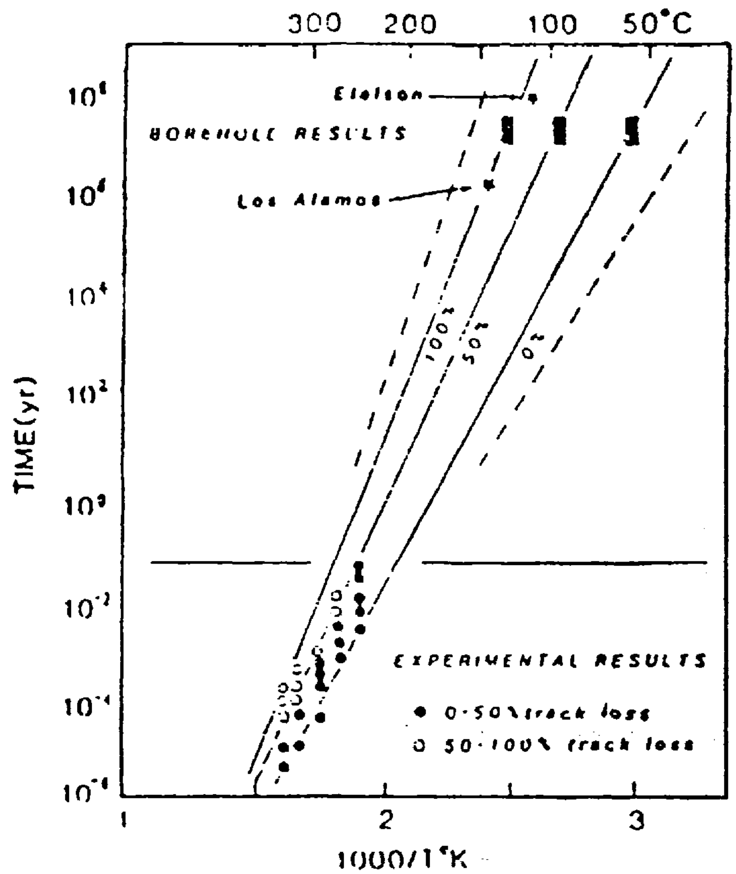


Figure A5. Arrhenius plot for fission track fading in apatite. Shows results from the Otway Group drill-hole data, laboratory annealing results of Naeser (1969) and results from the Eielson, Alaska, and Los Alamos, New Mexico deep drill-holes (Naeser, 1979). Dashed lines represent the 0 and 100% track loss lines extrapolated from laboratory annealing data alone (from Gleadow and Duddy, 1981).

A5). This plot shows that the temperature interval over which annealing occurs at geological time intervals is less than that predicted from laboratory studies. The variation of mean track length of confined tracks with change in depth and temperature down a drill hole has also been studied (Gleadow and Duddy, 1981; Gleadow *et al.*, 1983). Proportional lengths were expressed as a ratio of L (present measured length) over L_0 (the average length of fresh induced tracks in apatite). The results showed the mean lengths to be reduced relative to the original length of 16.4 ± 0.8 µm even in surface samples and that some long tracks still existed in samples that were 90% reduced in age. Plotting track length reduction versus temperature, they were able to locate the apatite partial stability zone in the Otway Basin as being between the temperatures of ~60°-70° and 125°C for times in the order of 10 m.y. They concluded that the unique contribution of apatite fission track analysis is the ability to define maximum paleotemperatures and variations in temperature through time. Gleadow and Duddy (1981) also observed that single grain ages varied considerably for samples in the partial stability zone. They suggested that this indicated that different apatites can have different annealing properties, presumably controlled by apatite composition.

The Effect of Composition on Apatite Annealing

Gleadow and Duddy (1981) proposed that chemical composition of individual apatite grains must play some part in the considerable spread of ***single grain ages*** from apatites subjected to temperatures within the partial stability zone. Green et al. (1985a) analyzed apatite grains from a single sample residing within the partial stability zone in an Otway Basin borehole. This sample displayed wide variation in single grain ages. The age for the bulk sample was 53 ± 2 Ma, but single grain ages ranged from 0 to 120 Ma. The single grain ages were plotted against the number of Cl atoms per $Ca_{10}(PO_4)_6(F,OH,Cl)_2$ molecule (Fig. A6). Cl-rich grains can be seen to be more resistant to annealing than Fl-rich grains.

Fission Track Length Annealing Studies

In a laboratory study of confined induced fission track lengths in a single, previously annealed, Durango apatite crystal, Green *et al.*, (1985a), determined a single activation energy (~1.64 eV). This implied a near parallelism of lines on the Arrhenius plot for various degrees of length reduction. Because the annealing characteristics of individual apatite grains are strongly controlled by Cl content, they suggested that the widely fanning Arrhenius plots could be the result of the superposition of a series of near-parallel

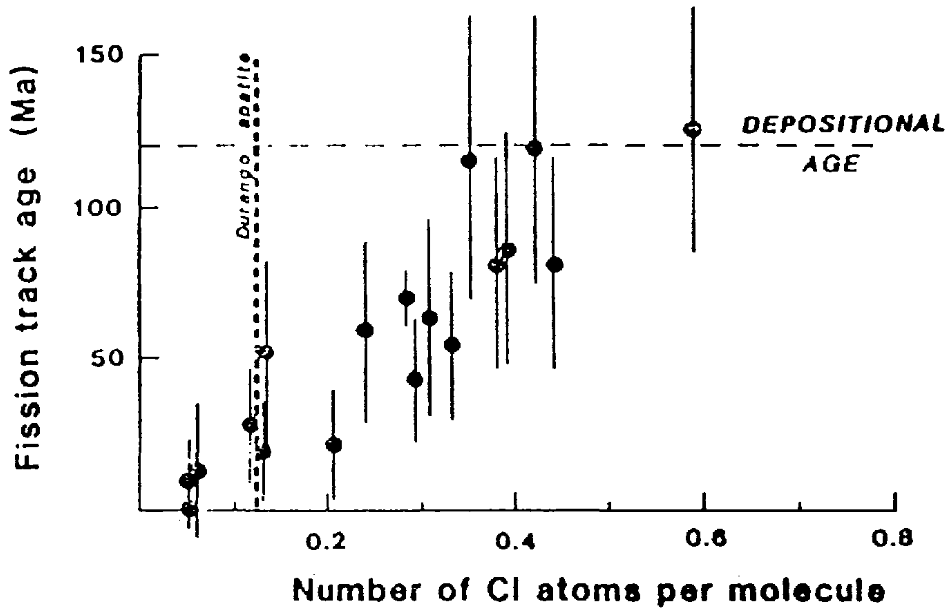


Figure A6. Variation of apatite single grain ages with composition. This sample is from the Otway Basin. Composition is expressed as a number of Cl-atoms in the (F, OH, Cl) group of the apatite molecule. This shows Cl-rich grains are more resistant to annealing than Fl-rich grains (from Green *et al.*, 1985a).

Arrhenius curves. Each curve would correspond to the range of compositions present and represent slightly different activation energies.

Green *et al.*, (1986) observed that in all annealed samples, the mean confined track length is always less than that in unannealed control samples. As annealing progresses, the mean length is reduced and the length distribution broadens, slowly at first, and then more rapidly below a length reduction (L/L_0) of ~0.65. In addition, the anisotropy of annealing becomes more pronounced in apatite as annealing progresses. Tracks aligned parallel to the crystallographic c-axis are more resistant than tracks perpendicular to it. As the mean length decreases, the only tracks preserved are those more closely aligned parallel to the c-axis. In heavily annealed samples ($L/L_0 < 0.65$) sequential etching indicated the presence of non-etchable (in terms of normal etch times) *gaps* along the length of a small proportion of tracks. These gaps, which delay the progress of the etchant during that process, are not common and may be breached with continued etching Green *et al.*, (1986).

A two-stage model for the annealing of fission tracks in apatite emerges. For mean lengths above ~10.5 μm ($L/L_0 \geq 0.65$) the form of the track length distribution changes only slightly with the degree of annealing because the anisotropy is not very pronounced. Below ~10.5 μm, the form of the confined track length distribution changes rapidly as annealing progresses. The dominant process causes a shortening of the etchable portion of the track from each end, with the rate of shortening increasing with increasing angle to the c-axis. For a given combination of temperature and time there is a characteristic maximum etchable length, which depends on the orientation of the track. As annealing becomes severe, gaps may appear in the etchable portions which may delay the progress of the etchant. With continued etching the gaps may be breached, allowing the characteristic etchable length to be revealed. The observed length distributions thus result from a combination of the anisotropy of annealing, and to a much lesser degree, the presence of gaps (Green *et al.*, 1986).

Laslett *et al.*, (1987) used the results of Green *et al.*, (1986) to determine whether the results were best explained by a parallel or slightly fanning Arrhenius plot. The best fitting parallel model accounted for only 96.7% of the variation of transformed length reductions. A slightly fanning model gave the best match, accounting for 98.0% of the variation.

For a slightly fanning Arrhenius model:

$$\ln(t) = A(r) + B(r)\,T^{-1}$$ (equation 20, Laslett *et al*, 1987)

where: t = annealing time
T = absolute temperature
$r = L/L_0$
A(r) = an unknown function of r subject to constraints that when t = 0 or T = 0, r = 1 so that: $A(1) = -\infty$

B(r) = a function where B is normally interpreted in terms of E/K where K is Boltzmanns constant and E is an activation energy

This model is difficult to fit since A(r) and B(r) are unknowns. Therefore, by statistical means they derived the following preferred model (see also Fig. 7):

$$\left[\left\{ (1-r^{2.7}) / 2.7 \right\}^{0.35} - 1\right] /0.35 = -4.87 + 0.000168T \left[\ln(t) + 28.12\right]$$

(equation 27, Laslett *et al*, 1987)

Measuring Fission Track Lengths

There are three ways of measuring fission track lengths:

[1] By measuring the projected lengths of tracks intersecting an exposed internal surface (Wagner and Storzer, 1972); [2] measuring the true length of tracks in an internal surface by measuring the vertical as well as the horizontal component of the track length and correcting for the dip of the track; or [3] measuring the true length of internal *confined tracks* (Fig. A7) which do not intersect the surface. Confined tracks, as defined by Lal *et al.* (1969), are tracks etched either via contact with a track which reaches the exposed surface or via a fracture or crack.

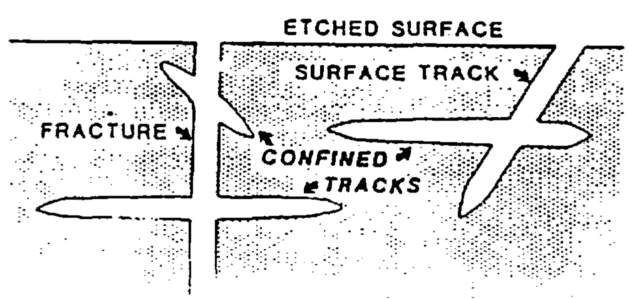


Figure A7. Confined fission track lengths as etched through fractures or other tracks (modified from Gleadow *et al.*, 1983).

To measure the true length of a confined track, one measures tracks present in the grain in a horizontal plane perpendicular to the line of sight. However, from a practical standpoint, it is possible to measure tracks that are not quite horizontal. Laslett *et al.* (1982) considered confined tracks with true dips <15° as horizontal because their measurement resulted in an underestimate of the actual length by only a few percent. With reflected light illumination, horizontal confined tracks exhibit a very bright image and can be easily located. This only occurs for tracks very close to horizontal. In transmitted light, a track is considered horizontal only if it remains in sharp focus along its entire length.

Confined tracks should be measured in prismatic grains (parallel to the c-crystallographic axis). This is because annealing in apatite is anisotropic causing tracks perpendicular to the c-axis to shorten faster than tracks parallel to the c-axis (Laslett *et al.*, 1984). Thus in a grain orientated parallel to the c-axis the whole range of track lengths will be present. In a basal section the mean track length will be shorter because the longest tracks will not be present.

In this study, confined fission track lengths in apatite were measured using the criteria outlined in Laslett *et al.* (1982, 1984) and Gleadow *et al.* (1986a, 1986b). To properly calibrate track length measurements I measured many track length standards with known distributions. Only after I displayed an acceptable level of competence determined by P.F. Green and A.J.W. Gleadow were the Alaskan samples measured for this study.

APATITE FISSION TRACK THERMAL HISTORIES

As previously discussed on page 29, annealing of fission tracks in apatite can be used to determine the thermal history of a sample. Gleadow and Duddy (1981), in a study of the annealing properties of apatite from subsurface samples in the Otway basin of southeastern Australia, defined a temperature range over which fission tracks anneal. In the Otway

Basin, apatite ages and mean track lengths began to decrease at ~60°C and reached 0 at ~125°C (Fig. A4). The entire apatite partial stability zone was therefore revealed and defined as ~60-125°C (based on the data in Fig. A4). Green (1986), presented data in which some annealing occurs even at ambient surface temperatures.

Track Length Distributions

Heating through the apatite partial stability zone, as track densities and mean track lengths decrease with increasing temperature, track length distributions have characteristic distributions relative to their length of residence time within the partial stability zone (Fig. A8). The transition from unaffected ages through partial overprints to total resetting is reflected in the shape of the track length distribution. For samples that were subjected to lower temperatures in the partial stability zone, track length distributions show a high mean

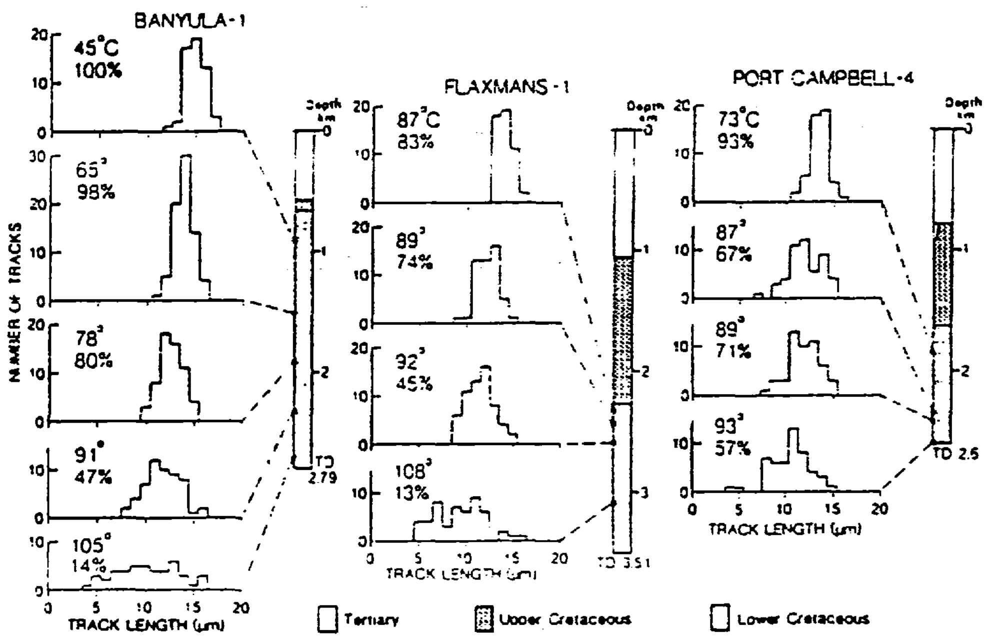


Figure A8. Fission track length distributions observed in apatites from the Otway Basin, South Australia, at various depths (temperatures) in three drill-holes. Estimated formation temperature and the percentage to which the apparent fission track age has been reduced is also shown (from Gleadow *et al.*, 1986a).

length with a low standard deviation. As temperature increases the length distribution broadens. This results in a decrease in the mean length and an increase in standard deviation. Samples from the base of the partial stability zone show very broad and relatively flat length distributions with mean lengths ~50% of the unannealed mean length. The maximum track length seen in the samples (~16 μm) doesn't change because new tracks are continually being formed.

Several possible patterns of track lengths in apatites arising from distinct thermal histories as described by Gleadow *et al.*, (1983) are shown in Figure A9. This Figure shows a number of hypothetical temperature vs. time plots and the resulting track-length distributions. The examples A-C show simple burial histories giving unimodal apatite length patterns essentially in equilibrium with different levels in the partial stability zone.

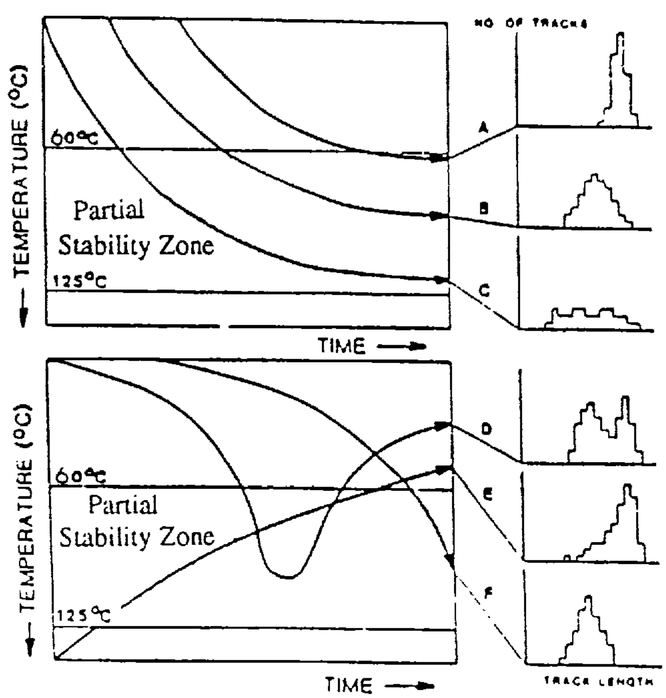


Figure A9. Idealized time-temperature paths with the resultant apatite track length distributions. See text for explanation (modified Gleadow *et al.*, 1983). The 60°C value for the upper boundary of the partial annealing zone is based on the work of Wagner *et al.*, 1977.

Examples D-F show a bimodal length distribution resulting from a past heating event, a skewed distribution typical of slow cooling through the partial stability zone, and an entirely shortened unimodal distribution produced by a recent temperature increase.

Bimodal distributions consist of two major length components: those that were annealed during a heating event and those that have formed since cooling to lower temperatures. By statistically separating the two components and estimating the contribution of the later group to the age of the mineral, the timing of the heating event can be estimated. Skewed distributions are essentially the summation of the three length distributions shown in simple burial. The shortened distribution resulting from a recent temperature increase is produced when all previous tracks are shortened together.

Gleadow *et al.* (1986b) determined apatite fission track length distribution patterns for a number of geologic environments. They divided confined track length distributions into five characteristic shapes (Fig. A10):

(1) Induced Track Length Distributions. Induced track length distributions from many apatite samples have mean track lengths which fall within a narrow range between 15.8 μm and 16.6 μm and have standard deviations of ~0.9 μm (Fig A10a). It is reasonable to conclude that induced tracks in all apatite samples will have a distribution typified by a mean of ~16.3 μm and a standard deviation <1 μm (Gleadow *et al.* 1986b). Track length distributions of spontaneous tracks from a wide variety of different apatites can therefore be compared without the need to refer back to lengths of induced tracks in the same apatite sample (Gleadow *et al.* 1986b), as had been previously suggested by Green (1980).

(2) "Undisturbed Volcanic" Distributions. These distributions are characterized by mean lengths between 14.0 and 15.7 μm and standard deviations from 0.8 to 1.3 μm (Fig. A10b) although most range from 0.8 to 1.0 μm. This type of distribution reflects rapid cooling after formation, and subsequent exposure to temperatures <50°C (Gleadow *et al.*

1986b). An undisturbed volcanic-type" length distribution can also be found in rocks of non-volcanic origin, where this distribution is diagnostic of a rapid cooling, followed by residence at low temperatures (<50°C).

(3) "Undisturbed Basement" Distributions. This form of distribution (Fig.A10c) is typical of plutonic rocks and high-grade metamorphic rocks that formed at high temperatures (>500°C) deep within the earths crust, were uplifted, and have now cooled to ambient surface temperatures. They are characterized by a distinct negative skewness, mean track lengths of ~12.5 to 13.5 µm, and standard deviations of ~1.3 to 1.7 µm.

(4) Bimodal and, (5) Mixed Distributions. These are characteristic of thermally affected, but not totally overprinted, samples. A "mixed" distribution reflects a partial thermal overprint which may become more prominent to form a "bimodal" distribution (Fig. A10d and A10e).

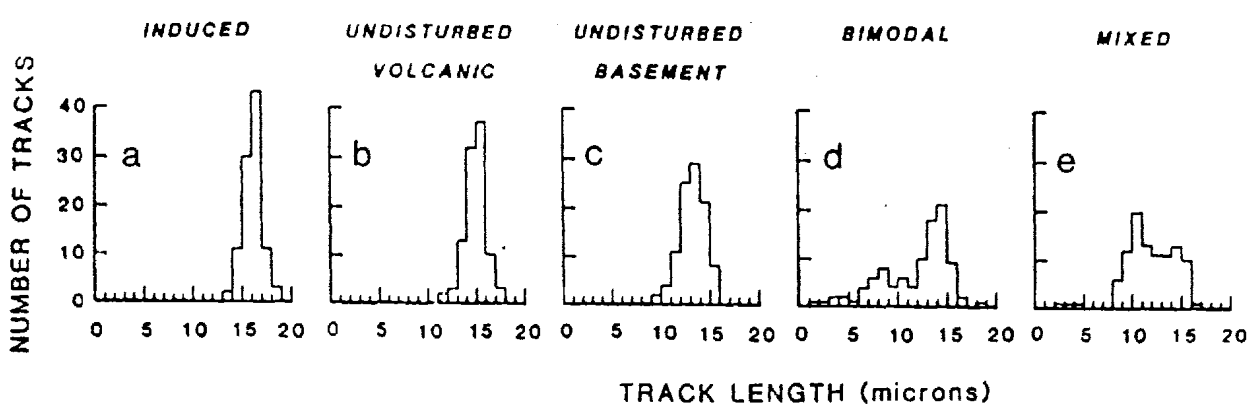


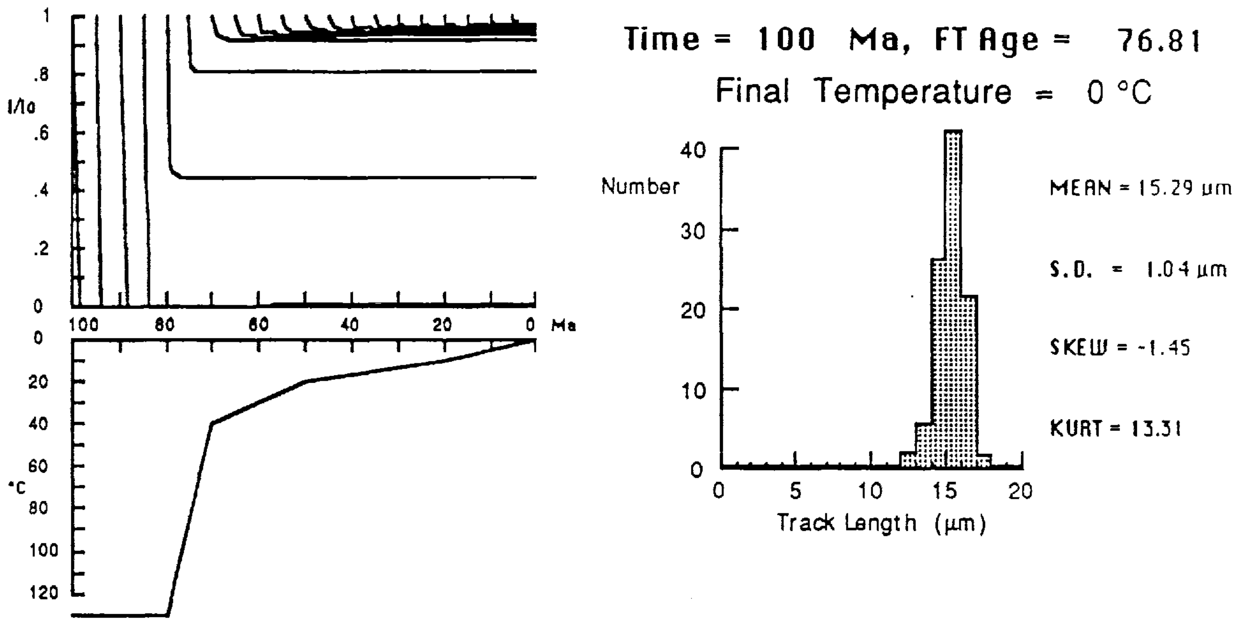
Figure A10. Characteristic apatite confined track length distributions for different thermal histories. See text for explanation (from Gleadow *et al.*, 1986b)

Upon completion of my results, the Alaskan sample track length distributions were compared to the above length distribution models and to interpretations of various thermal histories (Green *et al.*, 1985b; Gleadow *et al.*,1986b; Gleadow *et al.*, 1986a) in order to work out the thermal histories for the Alaskan sedimentary sequences.

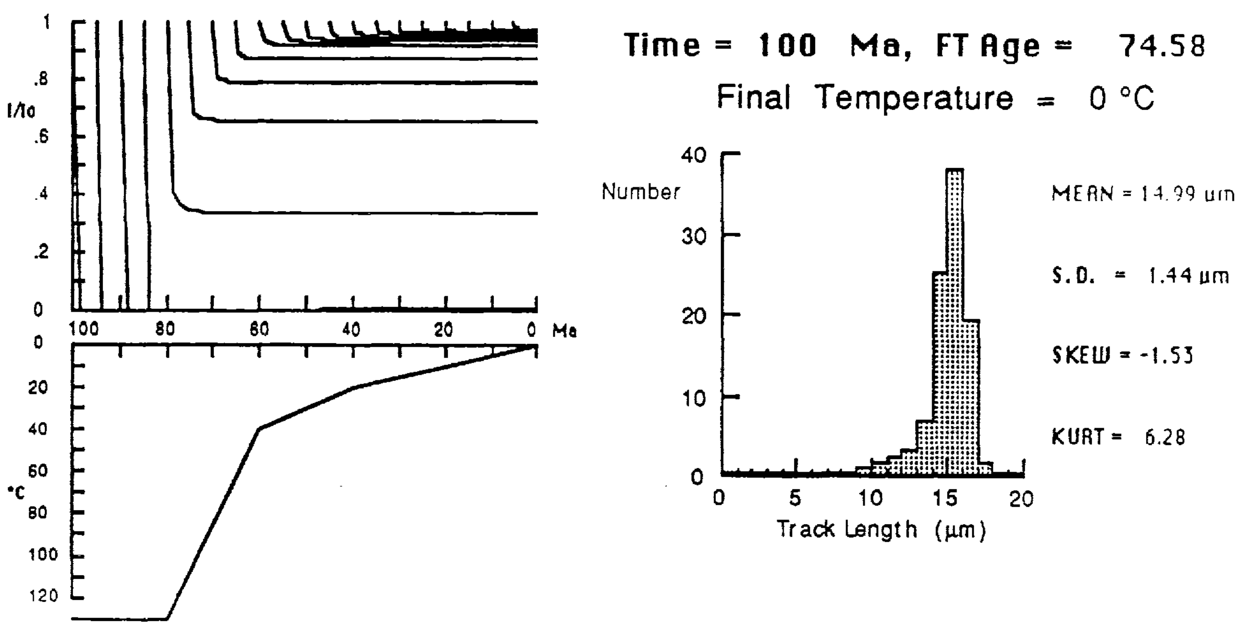
Thermal Modeling

Thermal modeling is an important tool in predicting a thermal history for a sample based on its apparent fission track age and the shape of its track length distribution. Figure A11 illustrates three examples with different rates of cooling and their resultant apatite ages and track length distributions as predicted by a thermal modeling program written by P.F. Green and A.J.W. Gleadow based on Laslett *et al.*'s. (1987) preferred model. In (A), rapid uplift resulting in cooling at a uniform rate from 130°C to 40°C over 10 m.y. is followed by much slower cooling to 0°C. The computer model produces a volcanic-type distribution for this cooling history. In (B) and (C), decreasing the rates of cooling (130°C to 40°C over times of 20 m.y. and 40 m.y. respectively) results in decreasing the mean track length and increasing the standard deviation. These effects result from the sample spending longer periods of time within the annealing zone (~60°-125°C) where more short tracks accumulate.

Figure A12 shows how sensitive this thermal modeling can be. In (A), the sample was at 130°C prior to a rapid cooling to 40°C between 50 and 60 Ma. The resultant track length distribution is a *volcanic-type* and contains no short tracks. In (B) and (C), the sample was at 120°C and 110°C, respectively, prior to rapid cooling and results in the preservation ofhigher percentages of shortened tracks. A small difference in the temperature prior to cooling (110-130°C) is easy to distinguish by the shape of the track length distribution. The sample at 130°C prior to cooling shows no short tracks. The sample at 120°C has a very small *tail* of tracks <12μm (~4%) and the sample at 110°C shows a larger tail of tracks <12μm (~8%).

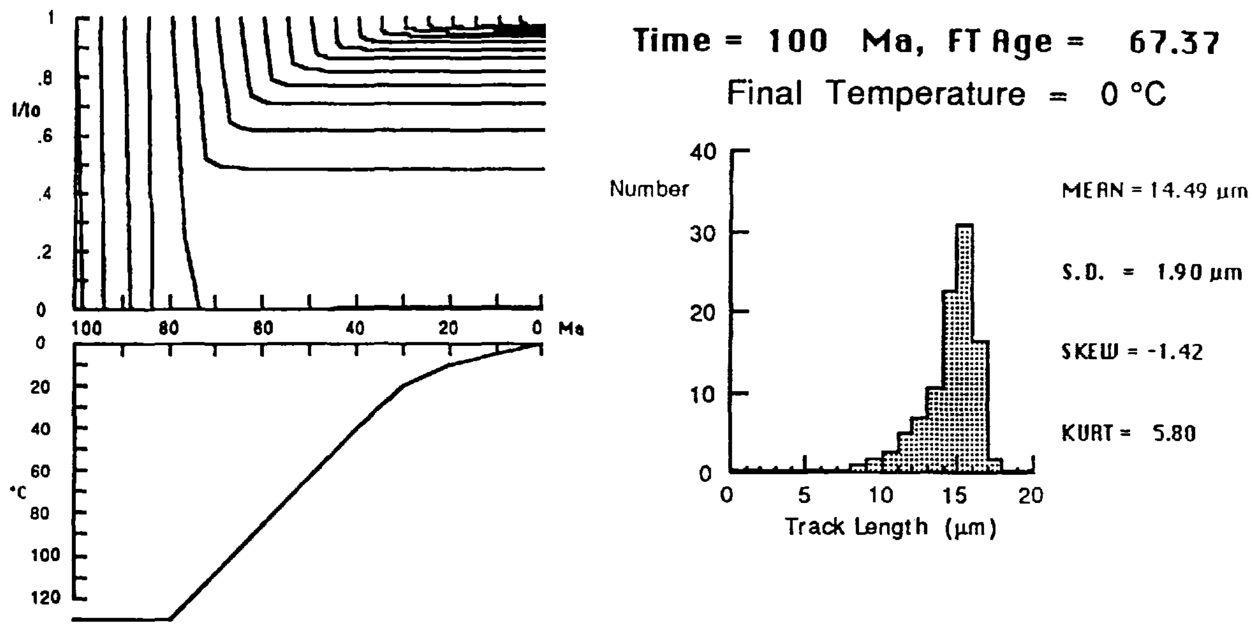


(A)



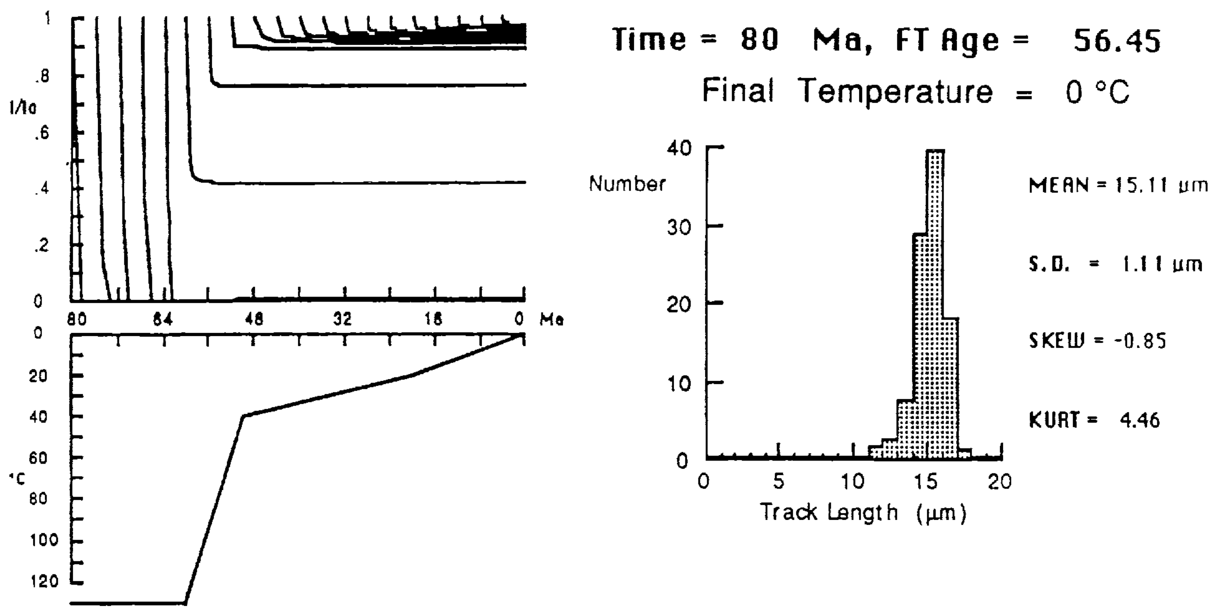
(B)

Figure A11. Figure caption on next page.

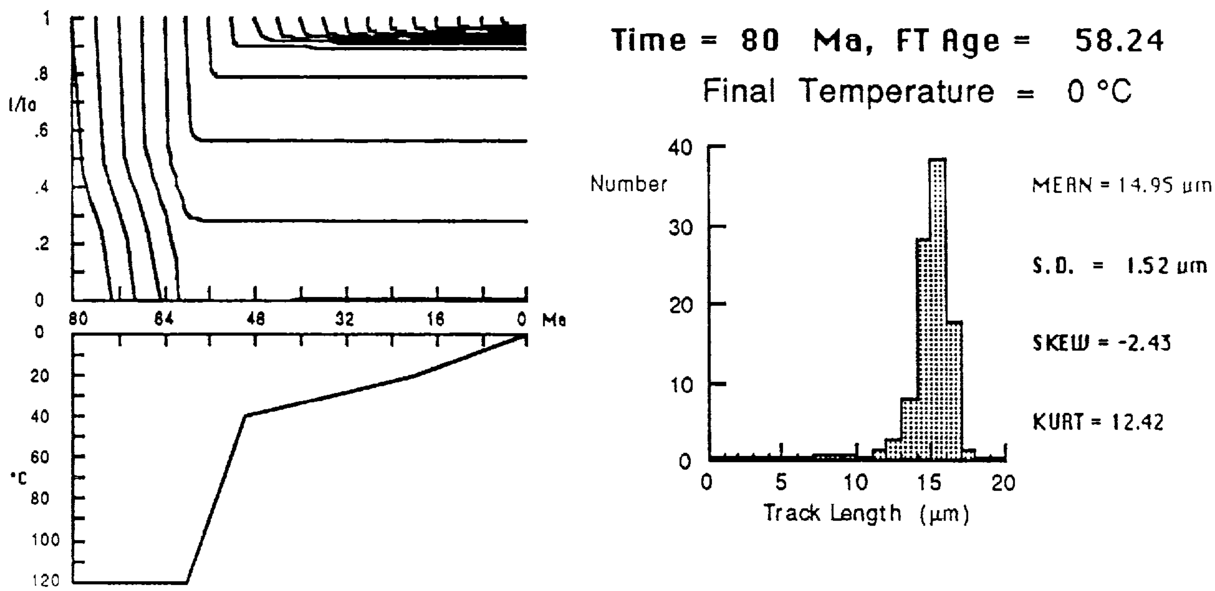


(C)

Figure A11. Apatite track length distributions resulting from different assumed thermal histories. Examples show expected distributions resulting from decreasing cooling rates (interpreted in terms of increasing rates of uplift). See text for explanation. These diagrams are produced from a program written by P.F. Green and A.J.W. Gleadow based on Laslett *et al.*'s (1987) preferred model of apatite fission track annealing. The thermal history being modelled is shown on the bottom left diagram in terms of a time-temperature path. "Time" represents the total time elapsed since fission tracks start forming. The history of track shortening is shown for 20 hypothetical tracks at different times (in each top left diagram), expressed as l/lo (measured length/ length of original track). The length distributions from each are summed to give the histogram on the right.

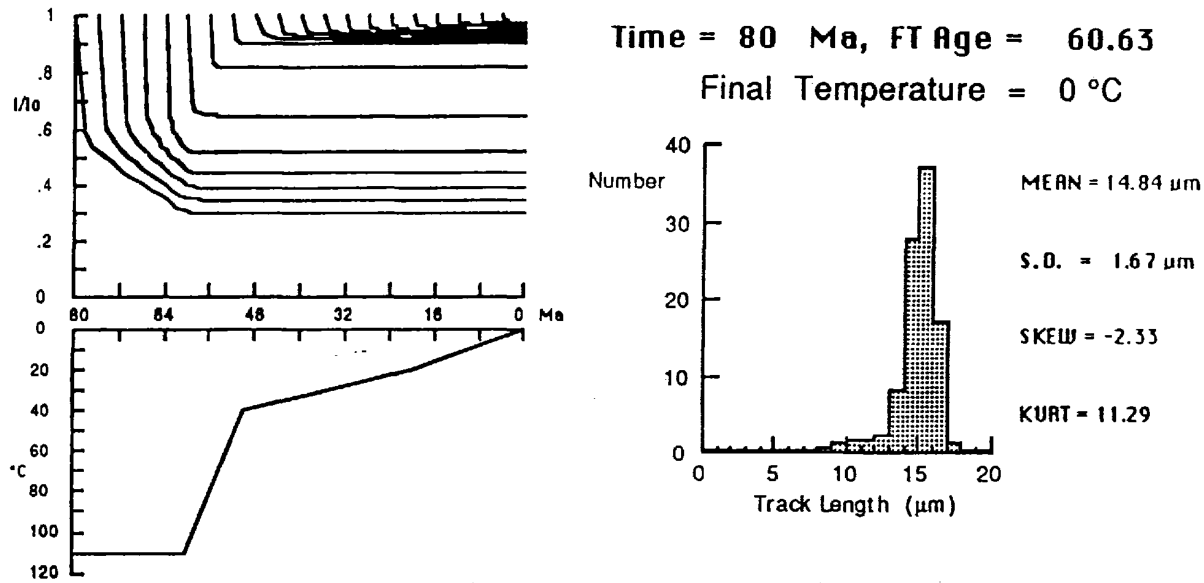


(A)



(B)

Figure A12. Figure caption next page.



(C)

Figure A12. Thermal modeling of different thermal histories prior to identical cooling histories. Examples show expected distributions resulting from rapid cooling from different initial temperatures. See text for explanation. These diagrams are produced from a program written by P.F. Green and A.J.W. Gleadow based on Laslett *et al.*'s (1987) preferred model of apatite fission track annealing. The thermal history being modelled is shown on the bottom left diagram in terms of a time-temperature path. The history of track shortening is shown for 20 hypothetical tracks at different times, (in each top left diagram), expressed as l/lo (measured length/ length of original track). The length distributions from each are summed to give the final distribution histogram on the right of each diagram.

Applications

An age and a track length distribution from a single sample can yield a relatively minor amount of information compared to a sequence of samples selected to reveal variations within a sedimentary section. The sequence may be taken from drill holes (e.g. Gleadow and Duddy, 1981), or taken from long vertical profiles in mountain ranges (e.g. Gleadow and Fitzgerald, 1987).

Apatite fission track analysis has been used to constrain the thermal histories of many different geologic settings. These include dating the emplacement of igneous bodies (e.g. Gleadow and Ollier, 1987), evolution of sedimentary basins (e.g. Gleadow and Duddy, 1984), evolution of continental margins (e.g. Moore *et al.*, 1986), uplift of mountain ranges (e.g. Fitzgerald et al., 1986), and "regional thermo-tectonic evolution" (Green, 1986). By using the observed fission track parameters and apatite thermal history models discussed above, it is possible to constrain the thermal history of a terrane. This approach has been applied to the Alaskan sedimentary rock units in this study.

APPENDIX B

APATITE FISSION TRACK ANALYSIS SAMPLE PREPARATION

INTRODUCTION

Sample preparation techniques described below are those in routine use by the Fission Track Research Group of the University of Melbourne Geology Department, recently described by Fitzgerald (1987). They have evolved over a 17 year period and have been improved by many people during that period. The techniques described below are those developed by A.J.W. Gleadow.

SAMPLE TREATMENT

Rock samples used in this study varied from about 3 to 6 kg. Sample numbers contain the year collected (87), my initials (POS) or those of John Decker (JD), and then number of the field location. Multiple samples from the same location were designated by A, B, or C. Sample numbers ranged from 87POS1A through 87POS117A and 87JD3B through 87JD87A. Weathering rinds were trimmed and the initial rock crushing was performed in the Geochronology Laboratory of the Geophysical Institute, University of Alaska, Fairbanks. The samples were then shipped to Melbourne for the remainder of the sample preparation. At every stage of the preparation, from crushing through mineral separation, pre-irradiation and then post-irradiation handling, measures were taken to insure cleanliness of equipment to prevent any possible contamination. A reference hand specimen was retained and a thin section was prepared for each sample.

ROCK CRUSHING AND MINERAL SEPARATION

Rock crushing and mineral separation procedures are summarized in Table B1 followed by a discussion of the subsequent steps.

Table B1. Rock Crushing and Mineral Separation Summary

(1) Crush to size range 200-75 μm.

(a) Large jaw crusher

(b) Bico Braun disk mill

(2) Wash thoroughly in water to remove fines (dust), or if the sample is too large, use a Wilfley Table to wash sample and concentrate heavy minerals.

(3) Oven dry at low temperatures (< 60° C).

(4) First magnetic separation.

(a) Frantz-full scale (1.9A), vertical paper funnel, removes ferromagnesian minerals

(b) Frantz-0.4A, vertical feed, removes biotite

(5) First TBE. Nonmagnetic fraction from (4b) into TBE, remove quartz, feldspar etc. as float.

(6) Second magnetic separation-sink from (5). Frantz at forward slope of 25° and side slope of 10°.

(a) Frantz-0.5A, removes biotite and epidote as magnetic fraction

(b) Frantz-0.8A, removes sphene and monazite as magnetic fraction

(c) Frantz-1.1A, removes sphene composites as magnetic fraction

(d) Frantz-full scale, magnetic cleanup

(7) Second TBE. Nonmagnetic fraction from (6d) into TBE, removes remaining quartz, feldspar, etc. as float.

(8) DIM. Sink from (7) into DIM, sink is zircon fraction, float is apatite fraction.

(9) Clean up apatite and zircon fraction.

(a) Apatite, Frantz-full scale, 2° to 5° side slope

(b) Zircon, Frantz-full scale, 0° side slope

TBE = Tetrabromoethane (sym) (specific gravity = 2.95-2.97)

DIM = Di-iodo methane (specific gravity = 3.32)

MINERAL MOUNTING, GRINDING, POLISHING, AND ETCHING TECHNIQUES

The following methods outline the procedure for mounting and preparing apatite for fission track analysis. The purpose of the mounting medium is to support the grains while they are ground, polished, etched, and eventually counted. Grinding exposes an internal surface, polishing removes the grinding scratches plus any surface imperfections, and etching reveals the tracks so they can be seen with a petrographic microscope. At all stages of preparation the sample numbers were labeled on the mounts.

Summary of Materials and Methods

Mounting medium:	epoxy on a glass slide. Araldite MY753 resin and HY956 hardener, 5:1 by volume or weight.
Grinding:	400 and 600 grit SiC waterproof abrasive paper on a wet rotating lap (400 rpm).
Polishing:	0.3 µm corundum polishing powder in a H_2O slurry on a nylon cloth lap rotating at 400 rpm (1:5 ratio, Al_2O_3:H_2O).
Etchant:	5M HNO_3 for ~20 (15-30) seconds at 20-22°C.

Mounting

Apatite grains were mounted in Araldite on a hot-plate at 120°C. Approximately 10 mg of 100-200 µm size grains are enough to adequately cover a 1 cm x 1.5 cm area so that the grains are not touching, yet not excessively isolated. Mounting with excessive grain density makes locating the grain image on the mica replica difficult. Once in the warm epoxy, the slurry was stirred with a needle to ensure that apatite grains sank to the bottom of the araldite. The slide was then left on the hot-plate for 5 minutes to cure the Araldite. Heating to 120°C for this very short period of time has been shown not to affect track lengths (Gleadow, 1984).

Grinding and Polishing

During this stage the slide was held in a specially made recessed brass holder. Excess epoxy was removed using the 400 grit paper. Internal surfaces of the grains were exposed using the 600 grit paper. In the grinding stage the slide is held stationary in one orientation. Mounts were polished for at least two periods of 45 seconds each.

Etching

Mounts were etched by placing two slides back to back, holding them together using tweezers and submerging them for 20 seconds in a beaker of 5M nitric acid. To stop the etching, they were submerged in a beaker of tap water and then rinsed with tap water. At this stage the mounts were trimmed down to a 1 x 1.5 cm size by snapping off the excess slide glass after scoring with a diamond pencil and ruler. Final trimming was accomplished using a rotating diamond-impregnated metal grinding wheel.

PRE-IRRADITATION SAMPLE HANDLING FOR THE EXTERNAL DETECTOR METHOD

Mount - Mica Pairs and Wrapping

The mounts were all trimmed to 1 x 1.5 cm at this stage. Pre-packaged rectangles (~50 μm thick x 1.3 cm x 0.85 cm) of low-uranium muscovite (<5 ppb) were used for the external detector. The sample number was scribed on the back of the mica prior to wrapping. The mount-mica pair was then placed in an envelope of heat shrink polythene/polyester laminate plastic using tweezers and then sealed using a heat sealer. The envelope corners were trimmed off to allow air to escape when the heat-shrinking takes place. Heat shrinking was done between two pre-heated glass slides on the hot plate at ~100°C. Considerable care was necessary at this stage to ensure the mica was aligned correctly over the mount, not overlapping the edges of the glass, and that good contact was achieved between the mount and the mica. Pinpricks were used to mark the corners of the mount-mica pair for use during the coarse alignment procedure on the Autoscan™ stage. Standard glass-mica pairs (for determining ρ_d, the standard track density) were wrapped in the same way.

The Irradiation Package

Up to 15 mount-mica pairs, all labeled and in known order, were placed in a stack with a standard glass-mica pair at either end for monitoring the neutron fluence. The stacks were wrapped tightly in Al-foil, the top labeled and placed in a high-purity aluminum irradiation tube. It is important to know the order of the samples within the tube so that if a fluence gradient is measured by the standard glasses at either end of the package then individual standard track densities can be assigned to individual mount-mica pairs.

Neutron Irradiation and Fluence Monitoring

Neutron irradiations were carried out in the X-7 position of the Australian Atomic Energy Commission HIFAR Research Reactor, Canberra, which has a well thermalized flux of $\sim 3 \times 10^{12}$ $ncm^{-1}sec^{-1}$. No flux gradients were detected from any of the 4 packages when using between 12-15 mount-mica pairs and 2 standard glasses (package thickness ~5 cm). Thermal neutron fluences were monitored by recording the standard track density in the mica external detectors placed over standard glass discs of the National Bureau of Standards (NBS) reference glass SRM612 (~50 ppm U). The standard neutron dose requested for the apatite packages was 1×10^{16} neutrons cm^{-2}. The apatites from the ANWR region were of such low uranium concentration (5-30 ppm U) that future irradiations should be given higher neutron fluences.

POST-IRRADIATION SAMPLE HANDLING

After irradiation, the mount-mica pairs were removed from the irradiation tube and unwrapped when a safe level of radiation was achieved. Micas were etched in 40% HF for 20 minutes, thoroughly washed overnight in tap water, and then allowed to stand for at least 12 hours. This allowed evaporation of any residual HF and therefore prevented any possible damage to microscope objectives. The mount-mica pairs were mounted on 1 x 3 inch glass slides using epoxy (Figure B1). Care was necessary at this stage to ensure the pairs were aligned in a mirror-image configuration and that the mica was not glued face down. The micas that were put over the standard glasses were mounted together on a separate slide.

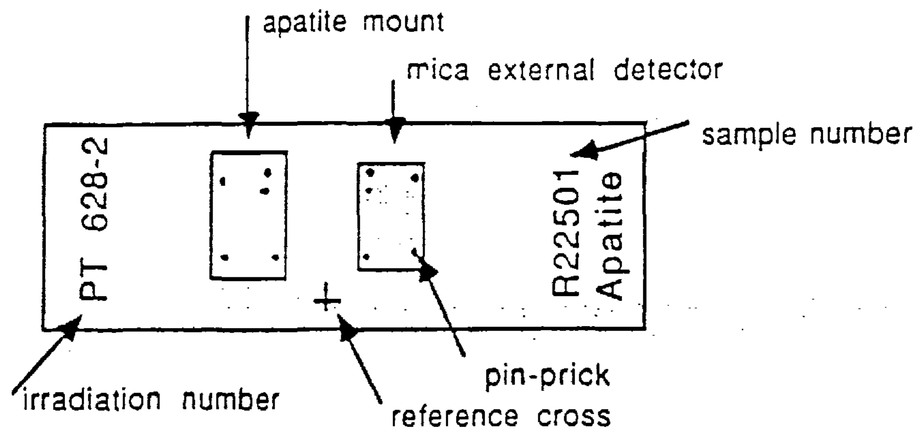


Figure B1. Mount/mica pair as mounted on a glass slide ready for counting and measuring track lengths. Pin pricks are used during coarse alignment and the scribed cross is used as the reference point for automated alignment (from Fitzgerald, 1987).

MICROSCOPE EQUIPMENT AND COUNTING PROCEDURES

Fission Track Ages

A Zeiss Universal microscope system, equipped with dry, epiplan objectives mounted on a revolving nose turret, was used for all fission track counting. Objectives used were corrected for use without cover slips. The 80x objective used for counting had a numerical aperture of 0.95 and the condenser had a numerical aperture of 1.4. The tube factor was variable using an Optivar magnification chamber, either 1.25x, 1.6x, or 2.0x being available. A Zeiss KPL wideangle binocular eyepiece with a magnification of 12.5x was used. A 10 x 10 grid located in one of the eyepieces was used for counting tracks over a known area.

Fission tracks were counted at a total magnification of 1250x (80 x 1.25 x 12.5 = objective magnification x tube factor x eyepiece magnification). The size and area of the grid in the eyepiece was calibrated using a diffraction grating (stage micrometer), one line on the diffraction grating being equal to 1.5678 μm.

Standard track densities (ρ_d) were obtained by scanning across the mica external detector and counting the number of tracks in a given area at a given number of locations. Tracks lying on the lines defining the top and right side of each square in the grid were counted as being within that square. The exact position of a track was defined by the position of the track *head* (the intersection of each track and the exposed surface of the grain). The requested dose of 1×10^{16} neutrons cm^{-2} for NBS glass SRM612 usually gave a standard track density (ρ_d) of ~1.35-1.45 x 10^6 tracks per cm^{-2}.

A microcomputer-controlled Autoscan™ 3 axis motorized stage system (Gleadow *et al.*, 1982; Smith and Leigh-Jones, 1985) mounted on the Zeiss Universal microscope was used for counting fission tracks. This stage system permits the automatic location of matching points on the mineral mount and its mirror image on the mica detector. The co-ordinates of all counting sites are recorded relative to the position of a small cross scribed on the slide (Fig.B1). The mount and the mica were first roughly aligned using the pin pricks and then fine-tuned using distinctive grains and their images. Alignment usually took about 10 minutes and had a precision of 5-10 μm.

The mount was usually scanned using the 16x objective under reflected light to look for grains with good polishing scratches (indicating proper etching conditions on the crystal face). Once a good grain was found it was examined under transmitted light to determine whether it was suitable for counting (dislocation free, and not zoned). The area counted on each grain varied according to the suitable area available (area on individual grains ranged from 4 to 70 grids with each grid ~8.548×10^{-7} cm^2). This area had to lie within a one-track-length distance of the grain margin. Usually 20 suitable grains were located (or as many grains as possible up to 20) before counting tracks in the apatite (N_s) and in their muscovite replica (N_i). A mechanical hand counter was used to record the number of tracks.

Confined Fission Track Lengths

A drawing tube was attached to the Zeiss Universal microscope and the images of confined fission tracks were measured on a Hipad™ digitizing tablet. This tablet had been previously calibrated using a stage micrometer marked at 10 and 2 μm intervals. A light emitting diode was attached to the cross hairs of the the digitizing tablet's cursor so it could be more clearly seen. Only horizontal, confined fission tracks with clearly defined ends were measured. Confined tracks were located by scanning the mount using a 40x objective under reflected light. Horizontal confined tracks usually appear as highly birefringent, cigar-shaped tubes. Track lengths were measured using an 80x dry objective. 100 track lengths (or as many as possible up to 100) were measured in each sample. Locating this many on most of the samples took 2-3 hours but some particularly young or low-U samples took up to 4 hours.